THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Doctor of Philosophy (Soils)
DEGREE

Soil Science
FIELD

Soil Science
DEPARTMENT

TITLE: Mineralogical Trends along some Soil Catenae in Thailand

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THESIS

MINERALOGICAL TRENDS ALONG SOME SOIL CATENAE IN THAILAND

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy (Soils)
Graduate School, Kasetsart University
2006

ISBN 974-9835-71-9

Suphicha Thanachit 2006: Mineralogical Trends along Some Soil Catenae in Thailand.
Doctor of Philosophy (Soils), Major Field: Soil Science, Department of Soil Science
Thesis Advisor: Associate Professor Anchalee Suddhiprakarn, Ph.D. 230 pages.
ISBN 974-9835-71-9

This study of mineralogical trends along some soil catenae in Thailand was carried out at two locations in Northeast Thailand, with major emphasis on the spatial variation of morphological, physical, chemical, mineralogical and micromorphological characteristics of soils along the catenary transects. Soil profiles were sampled at six positions; on the summit (SU: Typic Kandiustult), shoulder (SH: Psammentic Paleustalf), upper midslope (UM: Psammentic Haplustalf), lower midslope (LM: Psammentic Haplustalf), footslope (FS: Oxyaquic Haplustalf) and toeslope (TS: Aeric Endoaqualf) for Nam Phong catena developed on sandstone in the upper part and shale in the lower part. Four profiles developed on residuum and colluvium derived from basalt on crest (CT: Rhodic Kandiustox), backslope (BS: Typic Kandiustult), footslope (FS: Typic Plinthustult) and valley floor (VF: Typic Endoaquert) were sampled on Khon Buri catena. The study included morphological, physical, chemical, mineralogical and micromorphological analyses according to standard methods. SEM/EDS analysis was employed to analyze thin sections and quartz sand grains. Clays were viewed under TEM to study clay mineral morphology. The concentrations of elements in the whole soil, sand, silt and clay were determined and statistically analysed using factor analysis to identify affinity groups of elements and samples.

Results of the study reveal that most of the soils are deep and highly developed, particularly the upslope soils. Their colors range from reddish on the uplands to grayish at the lowest position of the landscape, which indicates differences in drainage condition. Soils on Nam Phong catena have texture ranging from sandy to silty clay whereas soils on Khon Buri catena are clayey, representing the influence of parent materials. Except for their texture, the physico-chemical properties of upslope soils are not distinctly different for both catenae. Dominant characteristics of upslope soils include a generally acidic condition, low exchangeable bases, low available plant nutrient contents and low cation exchange capacity. However, upslope soils and those on lowest positions on catenae are significantly different for most properties. Soils on the lowest positions are alkaline having high exchangeable bases, moderate plant nutrient contents and high cation exchange capacity. Leaching and eluviation are considered the main pedogenic processes in the soils on the higher positions whereas cumulization is the major pedogenic process in the lowest position of the catena. The spatial distributions of clay minerals with catenary position are systematic as kaolin is the major clay mineral of upslope soils while 2:1 clay minerals dominate clay fraction of the soils on the lowest position. Quartz is major constituent in silt and fine sand fractions for both catenae. Apart from these minerals, hematite and goethite are present in the soils reflecting intense weathering and their occurrence is controlled mainly by redox conditions and pedoclimate. Factor analysis shows systematic differences in overall chemical composition between soils for both catenae. The small variations in the chemical compositions of upslope soils on Nam Phong catena are due to different degrees of weathering of the same parent rock whereas soil on the toeslope position has a quite different elemental composition which is possibly due to a different parent rock and also to authigenesis of minerals in this landscape position where leached ions accumulate. For Khon Buri catena, the element compositions for the whole soil and these size fractions vary in systematic manner from the crest soil to the valley floor soil with various degrees of similarity and diversity between soils. The element concentrations in each size fraction of soils and in soils on each landscape position can be attributed to differences in parent rock and differential weathering.

These results indicate that upslope soils on Nam Phong catena have formed on a veneer of mixed colluvium of sandstone and metamorphic rock over chemically altered sandstone. Authigenesis of clay and carbonate was occurred in the toeslope soil. All soils on Khon Buri catena have been formed mostly on residuum derived from basalt but at some positions on the slope colluvial materials exist over the weathered *in situ* materials. However, the difference of soils among catenary positions in this basaltic terrain are mainly caused by differences in the extent and types of weathering as affected by drainage conditions.

Suphicha Thanachit — A. Suddhiprakarn — 21 / Feb. / 06

Student's signature — Thesis Advisor's signature

ACKNOWLEDGMENTS

Firstly, I would particularly like to thank Associate Professor Anchalee Suddhiprakarn for her support, guidance and so many things, especially her patience with me in so many terms. Apparently, it was enormous at time. I would also like to thank Professor Irb Kheoruenromne for his endless encouragement and all knowledge given to me up till now and still. I really appreciate that.

Very special thanks to Professor Bob Gilkes from Soil Science and Plant Nutrition, School of Earth and Geographical Sciences, University of Western Australia for kindly helping me settle during the period I was in Australia. Moreover, I am very extremely grateful for his correction on my thesis writing and some idea of the modification in my thesis. Thanks to Dr. Pisoot Vijarnsorn from Land Development Department, Thailand as a committee member and also to Dr. Santhad Rojanasoonthon, Director of Research, Royal Project Foundation as an external examiner for their kind suggestions and comments.

My study would not have come to this stage without some big hands from Dr. Saowanuch Tawornpruek and Dr. Punyisa Trakoonyingcharoen who together fought through the hard time with me during our stay in Australia and helped me a lot in the context of my study, consulting, exchanging ideas and being very good friends. I really enjoyed and thank for those things you did for me. I am grateful for laboratory work helped by Vanida Panikron from Land Development Department.

Thanks to Pramualpong Sindhusen from Land Development Department for teaching me how to interpret the thin section samples and using facilities in his lab and also to Piboon Kanghae, a lecturer from Department of Soil Science, Kasetsart University for helping me during soil sample collection trip.

I really must also have to thank Dr Somchai Anusontpornperm for loads of thing.

I have to thank my entire colleague from Soil Survey Group, Department of Soil Science, Kasetsart University, particularly Dr. Wanpen Wiriyakitnateekul, Dr. Sumitra Watana, Wimolnan Kanket, Napaporn Wongpokhom, Naruekamon Janjirawuttikul, Prisana Suasamserm, Chuthamard Kaewmano, Thanapol Srisupha-olarn, Thonglor Suttisong, Srichalai Khunthon and Nuttaphorn Prakongkep for their support, pretty good friendship and help all the way through my study. Additionally, I would like to give a special gratefulness to the latter person for walking me back home almost every single late night.

Thanks to Nui Milton, Michael Smirk, Bingah Astuti, Naoko, Gary, Adam, Joko and Wawan, Soil Science and Plant Nutrition, School of Earth and Geographical Sciences, University of Western Australia for a warm friendship, using facilities and helping me out in the lab over there. I am grateful to Martin Sauder and Gregory D. Pooley for the help on using electron microscope in CMM lab.

I am grateful to The Royal Golden Jubilee Ph.D. Program, Thailand Research Fund, for the financial support of the study.

Final say, without any support and love from my lovely parents, my dad, mom, brothers and some others, I may not have come this far. I enormously appreciate that.

Suphicha Thanachit
February 2006

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MINERALOGICAL TRENDS ALONG SOME SOIL CATENAE IN THAILAND

INTRODUCTION

Factors of soil formation have been considered to include parent material, climate, organism, topography, time and some specific local factors. These factors influence characteristic of soils (Jenny, 1941; Buol *et al.*, 1989). Thus soils are product of a complex interaction of chemical and physical processes that is controlled by some of these factors, particularly the topographic factor, over time (Hall, 1983). Topography is an important factor since it encompasses different reliefs and different soil drainage conditions, which provide conditions for chemical and physical processes. The situation in the Tropics with respect to topographically controlled variations of soil properties is no exception (Young, 1976).

Many studies had been carried out on soils on slopes or on landscapes. Milne (1936) suggested the word "catena" to define sequence of soils on a landscape. The soil catena is divided into several components, each of which is characterized a specific soil related to specific erosional or hydrological conditions (Bushnell, 1942).

The association of soils on a landscape has been considered to indicate the effect of relief on soils. Each landscape includes positions of different relief; units can be identified as summit, shoulder, backslope, footslope and toeslope positions (Ruhe, 1960). These positions are related to different soil drainage condition. Differences in erosion and deposition processes relate to the transport of material and solution in the landscape (Gerrard, 1992). Therefore, they produce variable soil properties for example, organic matter content, clay content, soil profile characteristics including soil color (Applegarth and Dahams, 2001). Some soil properties commonly vary on a catena. The solum and A-horizon thickness increase downslope (James and Fenton, 1993; Agbenin and Tiessen, 1995). The coarse fraction decreases from the soil profile on the summit to those on the footslope position (Bonifacio *et al.*, 1997), generally coarse sand decreases whereas the amounts of clay, silt and very fine sand increase downslope (Ovalles and Collins, 1986). In addition, the organic carbon content increases downslope (James and Fenton, 1993; Applegarth and Daham, 2001). The color of soil on the upper part of a slope is more reddish than that on the lower slope (Waltman *et al.,* 1990; Weitkamp *et al.,* 1996) as soils on well drained upper slope positions lack redoximorphic feature but those on wet downslope positions have redoximorphic feature (dos Anjos *et al.,* 1995).

The soil minerals in catena may vary systematically depending on moisture and the degree of weathering. There have been several reports on soil mineralogy on catenae. Curi and Franzmeier (1984) found that soils on the upper part of a slope contain hematite and gibbsite but those on lower part of slope had goethite and kaolinite. dos Anjos *et al.* (1995) found that soils on the upper part of a slope contained goethite but those on lower parts of the slope had smectite and lepidocrocite. Results of studies on mineral formation in the soil clay fraction for some tropical catenary landscapes indicate that extremely weathered soils with bases being severely leached out will normally contain kaolinite. This is the situation in high positions on catenae where soils show marked profile development. On lower positions, in contrast, the soils contain smectite and sometimes carbonate (Boonsompoppunth, 1984). The presence of both hematite and goethite in soils is controlled mainly by water activity (Schwertmann and Latham, 1986).

Soil mineral components can play important roles in determining soil properties. Thus, knowledge of mineralogical changes in catenae is vital for understanding trends in properties for topographically related soils. The collective knowledge of this mineralogical and chemical changes in soils can be used to improve management of those physical and chemical properties of soils that relate to soil fertility in catenae. Ultimately, these soils will be improved and attain higher production.

OBJECTIVES

1. To identify morphological, physical, chemical, mineralogical and micromorphological properties of soils along catena transects.

2. To identify the changes of mineral type and amount in soils along catena transects.

3. To evaluate the weathering process that gives rise to the minerals present in soils and their association with landscape positions in catena transects.

HYPOTHESES

The soils on tropical catena reflect the interaction of soils stratigraphy and chemical processes operating at a landscape scale. Two working sub-hypotheses are as follows:

- Soils along catena are not from a single material as they are stratified, the strata may be separated by stone lines, and colluvium becomes finer downslope.

- Different authigenic minerals will be dominant in soils at different slope positions due to differences in soil condition on a slope.

LITERATURE REVIEW

Soil Catena Concept

The soil catena means the succession of soils from the crest or summit position to valley floor or toeslope position of a landscape under a similar climate. There are differences of soil properties due to difference in drainage condition and relief that are related to the differential transport of eroded materials together with leaching, translocation and deposition of mobile chemical constituents (Milne, 1936).

The Processes of Catenary Differentiation

The differences of soil sequences on catenary landscapes are generally related to difference in their positions and drainage characteristics (Gerrard, 1992). They provide erosion and deposition processes that are related between transport material and chemical content on landscape (Young, 1976). The result is reflected in the difference of soil properties such as organic matter, clay content and soil profile development (Applegarth and Dahams, 2001). These processes depend on complex interrelated factors such as amount and duration of rainfall, topographic characteristic, permeability of the soil, nature of the underlying material, vegetation cover and physical condition of the surface of the soils (Young, 1976; Hall, 1983; Fanning and Fanning, 1989).

In the initial stage of soil genesis, parent material accumulation is determined by the geomorphic processes that have influenced the catena (Pennock and Vreeken, 1986). Mass wasting and slope wash on doline sideslopes of the Valley and Ridge Province of Eastern Tennessee had provided a variety of sediments (Crownover *et al.*, 1994). Whereas soils within catena in the northeastern Andos of Peru displayed trends downslope that indicated mainly pedogenic in origin rather than due to erosion of upslope soils and deposition further downslope (Miller and Birkland, 1992). Journaux (1975) explained such textural distribution with climatic induced erosion and landslide. Soil erosion can remove topsoil on the upper slope position and exposed subsoil horizon (Pierson and Mulla, 1990). Most of the gravel free material is removed and transported downslope by erosion to colluvium footslope (Dijkerman and Miedema, 1988). On the steepest slope along some stream banks, lateral seeps are found where the water table meets the soil surface (Osher and Buol, 1998) and on the steep slope the high rates of erosion would keep the soil in younger stage (Darmody and Foss, 1982). In addition, soil creep and slope wash produce a thin mantle of colluvium on all sloping surfaces (Graham *et al.*, 1990). Soil creep also occurs more slowly under non-saturated condition (Crownover *et al.*, 1994).

The shape of slope can influence moisture distribution and sediment transport (Birkeland, 1999). The stratigraphy and the shape of the land surface control water movement in landscape (Evans and Franzmeier, 1986). The Oxisols-Ultisols relationship in Sao Paulo, Brazil is controlled by the changes in the geomorphology. As slope is developed due to a change in the base level of the lateral water flow process starts operating (Moniz and Buol, 1982) that lateral and base water flow is controlled by precipitation, relief, catchment basin size and shape, and permeability (Moniz *et al.*, 1982). Soil features resulting from iron movement in B-horizon vary across Madre de Dios landscapes in Peru as the result of different oxidation-reduction cycle (Osher and Buol, 1998).

Clay illuviation is an important soil forming process occurring at each landscape position (Stolt *et al.*, 1993). Eluviation of clay or selective erosion could be a primary process or processes in evolution of soil in the central part in an Oxisol-Spodosol toposequence of Amazonia, Brazil (Bravard and Righi, 1989). The light-colored horizons are the results from eluviation of organic and mineral colloids by movement of water (Soil Survey and Staff, 1975). Clay contents decrease along catena in Amazon basin that explained by lateral clay eluviation (Bostchek *et al.*, 1996). The alternate processes of desilication-resilication occur horizontally downslope along the toposequence in Sao Paulo, Brazil. This may in part corresponds to intial desilication process in the upper slope followed by a resilication or the weathering sequence in soil on the lower part of landscape (Moniz *et al.*, 1982).

The main pedogenic process in the catena on serpentinite in north–western Italy, are lessivage of clay, formation of different 2:1 type clays which depend on porosity and acidification caused by organic matter (Bonifacio *et al.*, 1997). The processes on Ustult-Aquult-Tropept catena in west Africa were reported to include the formation of various geomorphic surfaces, weathering, formation of plinthite, formation of ironstone, gravel, ferrolysis, clay illuviation and the formation of gravel free layer by termites (Dijkerman and Miedema, 1988).

The Environmental Condition on Catena

A soil on catena has variable moisture (Osher and Buol, 1998) due to the groundwater table which provide soil drainage classes (Gerrard, 1992). The soil drainage conditions have influenced the soil catena (Pennock and Vreeken, 1986). Groundwater table restrictive horizons on sloping landscape tend to move laterally downslope (Weyman, 1973; Soil Survey and Staff, 1975; Parlang *et al.*, 1989). The high relief of the region may result in lateral flow of perched water and solute (Reuter *et al.*, 1998). Soils ranging from dark-red Latosol to red yellow Latosol are due to depth of water table that responds to precipitation. During the rainy season, excess water is being stored in soils, causing water table levels to rise (Macedo and Bryant, 1987). Groundwater table measurements indicate that the same duration of waterlogging correlates with soil colors progressively lowers chromas and more yellow hues in the older landscape (Dijkerman and Miedema, 1988). The depth to water table decreases from the soil surface along the hillslope to the depression that increases duration and the relatively shallow depth of water table in the lower position due to runoff from summit to footslope positions (James and Fenton, 1993). Soils on higher landscape position have greater fluctuations in water table level compared with soil on lower landscape (Khan and Fenton, 1994). The seasonal moisture deficit results in the large fluctuations of the water table near the surface soil and it is responsible for the prominent redoximorphic features such as plinthite and iron concretion (Osher and Buol, 1998).

Agricultural significant difference such as natural drainage properties can be identified readily on the landscape. On eastern highlands of Papua New Guinea, soils on crest and valley floors are poorly drained and on midslope are imperfectly drained. The clayey texture induces slow permeability (Rijkse and Trangmar, 1995). On Mollisol catena in Iowa, soils on summit and shoulder positions are not saturated and have high chroma without redoximorphic feature due to deeper water table. Soils on toeslope and depression have the shallowest water table. They have a longest time of saturation and have B-horizon with gray matrices, bright mottles and Fe-Mn concretions. Soils on backslope position have an intermediate characteristic (Khan and Fenton, 1994). The effect of drainage on toposequence in the Allegheny Plateau, Pennsylvania tends to mask the presence of paleosol in the well drained landscape. The paleosol horizons are strongly oxidized and have significantly higher free iron oxide content (Waltman *et al.*, 1990).

The effects of the landscape position on soil properties seem to have been modified by the intensity of pedogenic process (Agbenin and Tiesson, 1995). Soil development and landscape lowering have been resulted from the combined effect of weathering and lateral transport of fine material (Koppi, 1981). Weathering could also function in the soils of the Oxisol-Spodosol toposequence in Brazil (Bravard and Righi, 1989). On Morine catena in northeastern Andes of Peru, weathering is masked at footslope. The degree of stone weathering shows trend with depth along this catena. Generally, stone weathering is greatest at the surface and decreasing with depth in each profile. The weathered stones occur at a greater depth in the profiles downslope (Miller and Birkeland, 1992).

In the toposequence of Allegheny Plateau, Pennsylvania, the color of red substratum varied with landscape position and soil drainage (Waltman *et al.*, 1990). Evans and Franzmeier (1986) found that soil water and O_2 regimes in soil reflected in the color patterns in soils on toposequence in north-central, Indiana. Soil chroma is the color component most responsive to the oxidation state of Fe compounds shows a trend of increasing grayness with increasing duration of saturation. Weitkamp *et al.* (1996) reported that soils in the upper slope of Vernal pool catena has 5YR hues, while those in the lower slope position have 10YR hues and low chroma. The 5YR hues, which are indicative of hematite and oxidizing condition prevails in well drainage condition. The low chroma generally reflects a reduced condition. In addition, water moving downslope through or above the basalt may accelerate weathering of Fe bearing silicate minerals, releasing Fe^{2+} into solution. Ferrous Fe precipitating from solution usually produces amorphous Fe oxide (Wang *et al.*, 1989).

Physical Properties of Soils on Catena

The residual parent material varies slightly depending on landscape position which material at surface identified as colluvium or local alluvium that had moved to downslope position (Stolt *et al.*, 1993). The downslope increase of thickness and a depth of A-horizon and solum thickness (James and Fenton, 1993; Kirkby *et al.*, 1997) can be explained by the effect of erosion on the upper slope and deposition at the downslope position (Agbenin and Tiessen, 1995). Climate and topography influence soil morphology in semi-arid condition. There is a decrease in the amount of total sand and an increase in the amount of silt, clay and very fine sand in the downslope area (Boonsompoppunth, 1984; Ovalles and Collins, 1986). The coarse fractions decrease from the profile on summit to those on footslope (Bonifacio *et al.*, 1997). The Ck–horizon of soil on the toeslope, footslope, backslope and shoulder positions have higher clay content than that of the summit position which is probably due to erosion and deposition processes (Honeycutt *et al.*, 1990).

The textures of the surface horizons range from sandy loam on upper slope to silt loam on the lower slope was found in the hillslope derived from shale in northern Ghana (Abekoe and Tiessen, 1998). On a granite landscape, fine earth textures are uniformly sandy loam, both with depth and throughout the landscape (Sommer *et al.*, 2000). Most properties of the soils in upper Amazon basins appear to be controlled by the texture of their sedimentary parent material and by their position on landscape. The textural variations, characteristics of fluvial deposition environment result in soils of greater different particle size classes occurring side by side. The result of a studies by Osher and Buol (1998) on soil texture in Peru indicated that the variation in texture affects the streams on the landscape, the position on landscape and soil moisture. In addition, the decrease of soil potentials in the Itacoatiara Vicinity Amazonas in Brazil from the top to the lower position is mainly due to the variation of texture (Bostchek *et al.*, 1996).

The bulk density values of soils on a catena increase downslope in Sao Paulo, Brazil (Moniz and Buol, 1982). The decrease in bulk density values of soil aggregates is relative to sand grains (Pennock and Vreeken, 1986). Bulk density also indicates soil structure (Moniz *et al.*, 1982) and reflects the degree of soil development. On serpentinite catena, soils on the top of the hill have a composition that is more similar to the parent material than soils on footslope position (Bonifacio *et al.*, 1996).

Pierson and Mulla (1990) studied soil aggregate stability on landscape position of Palouse, Washington. They found that soil at a lower slope position has more aggregate stability than that at the upper part of slope. This is probably due to a result of erosion and the reduction in organic carbon content, inducing a reduction in aggregate stability. Organic carbon is important factor influencing the aggregate stability (Rodman, 1988; Pierson and Mulla, 1989). Fe_2O_3 content of the soil is also important factor in promoting aggregate stability but amorphous Fe is only weakly correlated to aggregate stability (Kemper and Koch, 1966). On Vernal Pool catena in southern California, soils on summit and backslope positions are shallow and coarse loamy. They are Entisols. Footslope soils are clayey Alfisols with strong prismatic structure, whereas toeslope soils are Vertisols with strong angular blocky structure and with the presence of slickensides (Weitkamp *et al.*, 1996).

Generally, the lower part of the toposequence is wetter than that of the upper part. The footslope and toeslope have the highest soil water content due to runoff from the upper slope position (Pierson and Mulla, 1990). Kirkby *et al.* (1997) studied the hydraulic conductivity in long core in the toposequence of the South, Australia. They found that the flow pathway in long core on the upper position difference from that on footslope position. The K_{sat} value for footslope B-horizon is only half of that for the upper slope. So the longer residence time of water in footslope as compared to that of the upper slope is probably due to a combination of increased length of core and reduction bypassing flow.

Chemical Properties of Soils on Catena

Organic carbon content decreases downslope on Oxisol-Spodosol toposequence in Brazil (Bravard and Righi, 1991) and on the slopes of Amazonia Brazil (Bostchek *et al.*, 1996), whereas the organic carbon content increases downslope in northeastern Pervian Andos (Miller and Birkeland, 1992) and in a catena in Iowa (James and Fenton, 1993). Result of erosion and reduction in organic carbon content induces the reduction of soil aggregate stability (Rodman, 1988; Pierson and Mulla, 1989, 1990).

Soil finers were slightly to moderately acid in all profiles except in the one on lower slope where pH was slightly alkaline, which is generally found in Vernal Pool catena in southern California (Weitkamp *et al.*, 1996) and the Inceptisols-Alfisols hillslope derived from shale in northern Ghana (Abekoe and Tiessen, 1998). Electrical conductivity (EC) value does not vary significantly with slope position on Vernal Pool catena (Weitkamp *et al.*, 1996).

On Oxisols-Spodosols toposequence in Brazil, difference in the amounts of major elements are evident among the members. SiO_2 increases from Oxisol (upper part of slope) to Spodosol (lower part of slope) indicates a greater relative accumulation of SiO_2 in the lower part of the sequence (Bravard and Righi, 1989). Exchangeable Ca, Mg, and K increase uniformly downslope where Mg shows the greatest increase in the lower slope relative to other bases. Therefore cation exchange capacity (CEC) is greatest downslope (Weitkamp *et al.*, 1996). The high base saturation in the topsoil of the footslope profile may be due to the accumulation of fresh colluvium (Rijkse and Trangmar, 1995). SiO_2 content increases downslope but Al_2O_3, Fe_2O_3 and TiO_2 have a tendency to decrease downslope on toposequence of Amazonia, Brazil (Bravard and Righi, 1989). Fe, Mn, Si and bases are concentrated downslope on catena in the Northeastern Andes of Peru (Miller and Birkeland, 1992) as a result of lateral and base water flow action affecting mainly the soils in footslope (Moniz *et al.*, 1982). Effective cation exchange capacity (ECEC) values correlated with Al and Fe suggesting that surface reactions and exchange properties of the soil might be governed by amorphous aluminum, and iron oxides are probably present as surface coatings on clay (Agbenin and Tiessen, 1995). On the upper and middle parts of catena in Itacoatiara Amzonas, Brazil, the exchangeable Al fills up the main portion of ECEC. The Al saturation decreases on the lower part and finally disappears in the last profile of the catena. (Bostchek *et al.*, 1996). The percentage Al saturation of ECEC increases with a poorer drainage on Ustult-Aquult-Tropept catena in west Africa (Dijkerman and Miedema, 1988). The presence of the mineral dissolution on Oxisols-Ultisols toposequence in Brazil, were reported as being produced by base water flow (Moniz and Buol, 1982). Ojanuga et al. (1976) studied free iron of a toposequence in Nigeria. They suggested that iron oxides not only move vertically downward but also laterally downslope in soils. The free iron oxide content of soil increases with increasing depth in the well-drained soil and it also increases laterally in the toposequence. The free iron oxide content of poorly drained soil is lower than those of well-drained soils. This may be due to the repeated removal of dissolved free iron oxides from the soil, possibly in laterally seeping groundwater.

Some physicochemical properties of A-horizon in soils vary on the Amazonia toposequence. These differences could account for the difference in the amount of P-leached due to different thickness of the A-horizon (Bravard and Righi, 1991). On hillslope in northeast Brazil, the total phosphorus of the soil finers in surface horizon of the upper slope and shoulder positions are usually large, that it is more than that of the footslope. The greater Ca-P fraction of the upper and midslope top soils is accompanied by a greater exchangeable Ca than that in the lower slope (Abekoe and Tiessen, 1998). The greater secondary inorganic P reflects the increased weathering at the soil surface (Harrison *et al.*, 1994). Small available phosphorus contents of soil finers confirm the relatively high degree of weathering (Ibia and Vdo, 1993). The total phosphorus content was moderately low in the surface soil of an Ultisol hillslope in northwest Florida is probably due to low clay content and the relatively more intense weathering condition. Total phosphorus content also seemed to directly associate with the amount of clay on the lower landscape. This association may be the result of activity of the mineral dominant in the clay fraction (Day *et al.*, 1987).

The Mineralogical Trends on Catena

The chemical environment on each position on catenary landscape normally determines the kind and frequency distribution of clay minerals and oxides of iron and aluminum in soils. This is controlled by concentration of cations in soil solution at each position (Yaalon *et al.*, 1971; Kantor and Schwertmann, 1974; Fitzpatrick and Le Roux, 1977; Curi and Franzeier, 1984; Bhattacharyya *et al.*, 1992). Bases depleting environment of high rainfall, high leaching and well drainage induce kaolinite formation on older geomorphic surface. Whereas the high base and poorly drained conditions induce smectite formation (Vijarnsorn and Fehrenbacher, 1973; Gallez *et al.*, 1976; Boonsompoppunth, 1984). Oxides of iron and aluminum are product of intense weathering. Gibbsite normally occurs on the upper part on an Oxisols-Ultisols toposequence in Brazil and on Meihua mountain in China with high rainfall, intensive leaching by desilication process (Moniz and Buol, 1982; Jianfei *et al.*, 1993). Hematite generally forms in low moisture and high temperature while goethite formation favors high moisture and low temperature (Schwertmann and Latham, 1986).

The minerals in clay fraction are important in soils because they are related to other characteristics of soil such as physical and chemical properties and indicate degree of soil development (Juo, 1980; Spark, 1995; Murray, 1999). In tropical soils, physicochemical properties depend on the kinds and amount of clay minerals and oxides of iron and aluminum present (Gallez *et al.*, 1976; Young, 1976; Osher and Buol, 1998).

The minimal change in mineralogy occurs across the Upland/Tidal Marsh catena (Stolt and Rabenhorst, 1991). The clay content increases downslope on a catena of Iowa (James and Fenton, 1993). Clay content on catena in northeastern Andes Peru increases from the summit to the backslope and either decreases or remains constant from backslope to footslope (Miller and Birkeland, 1992). The clay content decreases along the slope in Itacoatiara Vicinity Amazonas, Brazil (Bostchek *et al.*, 1996) and in Whiskey Basin Wyoming, USA (Applegarth and Dahams, 2001) may be due to the erosion occurring in each position (Pierson and Mulla, 1990). Clay illuviation is most strongly expressed in the lower horizons and in poorly drained soil probably because of less mixing of soil materials by fauna (Dijkerman and Miedema, 1988). On Upland/Tidal Marsh catena, minerals in the argillic horizons are predominantly kaolinite, vermiculite, mica, smectite and quartz but the fine clay contains smectite and vermiculite, and quartz is completely absent (Stolt and Rabenhorst, 1991). A trend of increasing clay-total phosphorus values in soils located on successively lower landscape position may indicate horizontal translocation of phosphorus, either by overland flow or subsurface flow (Day *et al.*, 1987).

Quartz increases in soil from the upper slope to lower slope of the Oxisol-Spodosol toposequence in Brazil are attributed to a combination of hydraulic weathering and either or both of clay elluviation and selective erosion of that fraction (Bravard and Righi, 1989). Quartz may be transported by erosion to the soil at footslope and toeslope positions where it is in fact present only in the upper horizon (Bonifacio *et al.*, 1997). In soils of eastern Madre de Dois, Peru, a horizon with 100% quartz in the fine sand fraction occurs on the level upland and those with <100% quartz are from side slope and flood plains. The quartz grains observed in soil are rounded and finely pitted indicative of detrital transport (Osher and Buol, 1998).

For soil in Sao Paulo, Brazil, gibbsite content generally decreases downslope. The Alfisols at footslope have one-half the gibbsite content of the Oxisols on the crust (Moniz *et al.*, 1982). A decrease or even disappearance of gibbsite may be due to the formation of small amount of montmorillonite in poorly drained soil in footslope (Andrade *et al.*, 1976) since the presences of montmorillonite and low charge vermiculite depend on soil drainage condition (Bonifacio *et al.*, 1997). Gibbsite sediment also could resilicate to kaolinite or montmorillonite (Jackson *et al.*, 1948). Illite strongly decreases whereas kaolinite and interstratified clay minerals increase within Ustult-Aquult-Tropept catena in west Africa (Dijkerman and Miedema, 1988) due to illite is less stable than kaolinite in soil environment (Allen and Fanning, 1983). The weathering of a soil on serpentinite catena gives rise to low charge vermiculite in the upper and drier horizon or to give smectite when it is in poorly drained condition. Vermiculite in turn may be transformed to smectite under moister environment (Bonifacio *et al.*, 1997).

In soils on the Oxisol-Spodosol toposequence, amorphous iron increases from the upper part to the lower part of slope but the iron in silicate decreases downslope due to the increased effect of organic component. The Al_2O_3, Fe_2O_3 and TiO_2

decrease downslope. These results in the accumulation in form kaolinite for Al and in form of oxide for Fe and Ti (Bravard and Righi, 1989). Furthermore, iron or aluminum movement is a good indicator of clay movement in soil (Kirkby *et al.*, 1997).

On Sao Paulo catena in Brazil, soils became gradually more yellowish downslope indicating a decrease or disappearance of hematite (Moniz *et al.*, 1982) or a corresponding increase in goethite content (Bigham *et al.*, 1978). On the upper slope of Vernal Pool catena, soils as reflected by their 5YR hues are indicatives of hematite and by a low clay content dominated by kaolinite while soils on toeslope and basin have 10YR hues and low chromas, reflecting a seasonally reduced and iron oxide-poor environment (Weitkamp *et al.*, 1996). Soil chromas respond to the oxidation state of iron compound (Evans and Franzmeier, 1986). The soil colors are related to saturation and aeration because the redox reactions involving iron compound regulate the distribution and form of iron throughout the soil profile (Bonner and Ralston, 1968; Schwertmann and Latham, 1986). Whereas Suddhiprakarn *et al.* (1985) suggested that the form of iron oxide mineral may not be a conclusive criterion to judge by the color of the soil. The high degree of crystallinity of iron oxides in well drained profiles in Nigeria semiarid region is probably due to the high temperature condition and prolonged dry season (Juo *et al.*, 1974). The paleosol horizon varies in color and iron oxide mineralogy across the catena sequence on Allegheny Plateau, Pennsylvania (Waltman *et al.*, 1990).

Soils on the central plateau of Brazil form on basalt. Ustic moisture regime condition promotes the lower moisture content that it leads to higher average temperature on the upper position, which favors dehydration of ferrihydrite to hematite. In addition, silica moved downslope could explain the relatively greater content of gibbsite on the upper slope position and of kaolinite in the lower slope position. Thus, soils on the upper slope position have relatively high hematite and gibbsite contents and those in lower position have relatively high goethite and kaolinite content (Curi and Franzmeier, 1984).

Soils on toposequence of Maranhao State, northeastern Brazil, form on sandstone. Summit positions lack plinthite due to well drained condition. They are rich in smectite, probably inherited from the parent material, and goethites due to the oxidizing condition prevails. Shoulders are moderately well drained that favors formation of kaolinite. It has the largest concentration of total Fe, mostly goethite due to the oxidizing condition prevails. Footslopes are somewhat poorly to poorly drained. There are accumulations of bases as well as Si, favoring formation of smectite. Soils on this position exhibit the most redoximorphic feature and has a horizon in which the iron is strongly concentrated in ironstone and plinthite. Lepidocrocite is also dominant in this position. The absence of gibbsite is an indicator of the relatively low degree of weathering (dos Anjos *et al.*, 1995).

For the Oxisol-Inceptisol-Ultisol sequence in southeastern Brazil, soils on the summit and backslope positions are Oxisols. There are traces of altered feldspar and mica in sand fractions whereas the clay fraction contains a large amount of kaolinite, a little amount of goethite and trace of hallosite and hydroxy-Al-interlayer. The soils on shoulder and toeslope positions are Inceptisols, which soils on shoulder have a little amount of mica in sand and clay fractions. The other on toeslope has a very low amount of goethite but the greatest amount of mica in clay fractions. Soils on a footslope position are Ultisols, in which the sand fractions contain trace of halloysite and altered mica. They have a low amount of illite. Gibbsite can be detected in this position. In addition, some resistant minerals such as tourmaline, rutile-ilmenite, zircon, epidote and sillimanite are common in all positions (dos Anjos *et al.*, 1998).

MATERIALS AND METHODS

Geology Setting and Site Study

The Khorat Plateau in Northeast Thailand covers approximately 170,000 km^2 which is one third of the total area of the country (Parry, 1996). The Plateau is bounded to the North and East by the Mekong river, to the South by the Dong Rak mountain range and to the West by Petchabun and Dong Phrayayen mountain ranges. Regional topography is low (< 250 m MSL) and the surface is gently undulating and dotted by low hills and small shallow lakes. The regional plant cover consists of a range of deciduous to mixed deciduous communities. A large area is flooded during the wet season and in most parts soils are deficient in nutrients. The Khorat Plateau has received significant scientific attention by local quaternary geologists who consider it to have received an aeolian (loess-like) mantle of Late Pleistocene to Holocene age (Hoang Ngoc Ky, 1989; Udomchoke, 1989; Boonsener, 1991). Aeolian processes would be expected to have operated at much higher rates than present during the colder periods of the last and earlier glacial cycles. During glacial periods the paleo-environmental of the Khorat Plateau was clearly cooler and probably drier than at present but there is no evidence to indicate periods of extreme aridity in this region associated with glacial maxima (Penny, 2001). Subsequent to all aeolian deposition of sands bioturbation particularly by termites has modified this cover layer (mantle) (Löffler and Kubiniok, 1991, 1996; Sanderson *et al.*, 2001).

The representative Nam Phong and Khon Buri catenae are in Khon Kaen and Nakhon Ratchasima provinces respectively on the Khorat Plateau. The environmental setting of the soils on both catenae is given in Table 1. The locations of soil profiles in each soil catena and their geology are shown in Figures 1 and 2. The Nam Phong catena can be divided into 6 geomorphic positions: summit, shoulder, upper midslope, lower midslope, footslope and toeslope. Their altitudes are 209, 206, 202, 199, 191 and 180 m MSL respectively. Their coordinates range between 48 267414^E – 48 2678346^E and 18 55617^N – 18 55419^N from the highest position to the lowest position on the catena. The catena length is about 1 km. The Nam Phong catena has

Table 1 Environmental conditions of Nam Phong and Khon Buri catenae

Soil classification	Slope position	Parent material	Slope (%)	MSL (m)	Drainage	Runoff	Permeability	Erosion	Land use
1. Nam Phong catena developed on sedimentary rocks									
Typic Kandiustult	summit	old local alluvium	2	210	well-drained	moderate	moderate	moderate	cassava
Kandic Paleustalf	shoulder	wash over colluvium derived from sandstone	7	207	well-drained	moderate	moderate	moderate	cassava
Typic Haplustalf	upper midslope	wash over colluvium derived from sandstone	6	203	well-drained	moderate	moderate	moderate	cassava
Typic Haplustalf	lower midslope	wash over colluvium derived from sandstone	5	199	well-drained	moderate	moderate	moderate	cassava
Oxic Dystrustept	footslope	wash	6	192	moderately well drained	slow	moderate	moderate	cassava
Aeric Endoaqualf	toeslope	residuum derived fine grained sedimentary rock	1	180	poorly-drained	slow	slow	slow	paddy
2. Khon Buri catena developed on a basaltic lava corrosion undulating plain									
Rhodic Kandiustox	crest	residuum derived from basalt	0	275	well-drained	slow	rapid	slow	cassava, jack fruit
Typic Kandiustult	backslope	colluvium and residuum derived from basalt	3	236	well-drained	moderate	moderate	moderate	cassava, sugarcane
Typic Plinthustult	footslope	colluvium and residuum derived from basalt	3	233	well-drained	moderate	rapid	moderate	cassava, sugarcane
Typic Endoaquert	valley floor	colluvium and residuum derived from basalt	0	225	poorly-drained	slow	slow	slow	paddy

developed on sedimentary rocks of the upper Triassic to Cretaceous Khorat group and Lower Tertiary to Lower Pleistocene Krabi group. Soils from the summit to footslope positions are on the Khok Kruat Formation of the Khorat Group. The soil on the toeslope position is on quaternary deposits of the Krabi Group (Department of Mineral Resources, 1983). The Khok Kruat Formation consists of red to purplish gray bedded sandstone, siltstone and shale with interbedded calcareous conglomeratic sandstone, sandy limestone and calcareous siltstone which is mottled with purplish gray and greenish gray colors. The quaternary Khok Kruat floodplain deposit comprises unconsolidated silt, clay, sand and gravel (Suwanasing, 1972). Soils on the summit to footslope positions are under cultivated cassava fields (Figure 3a) but the main land use at the toeslope position of this catena is paddy rice (Figure 3b).

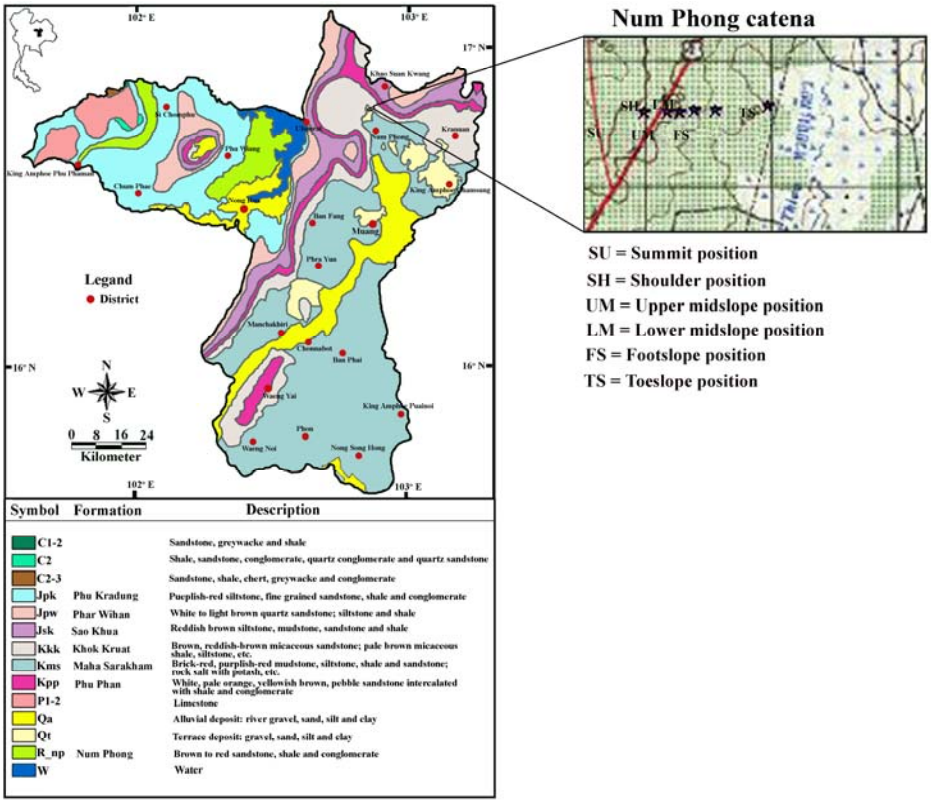


Figure 1 Geology of the study areas; the Nam Phong catena at Amphoe Nam Phong, Khon Kean Province, Northeast Thailand.

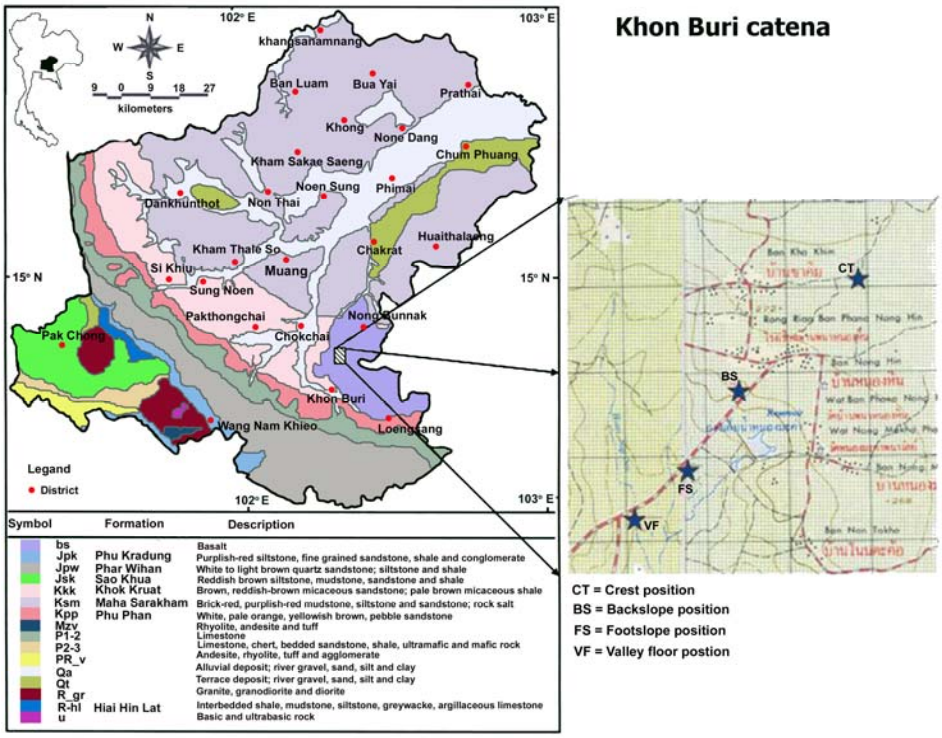


Figure 2 Geology of the study areas; the Khon Buri catena at Amphoe Khon Buri, Nakhon Ratchasima Province, Northeast Thailand.

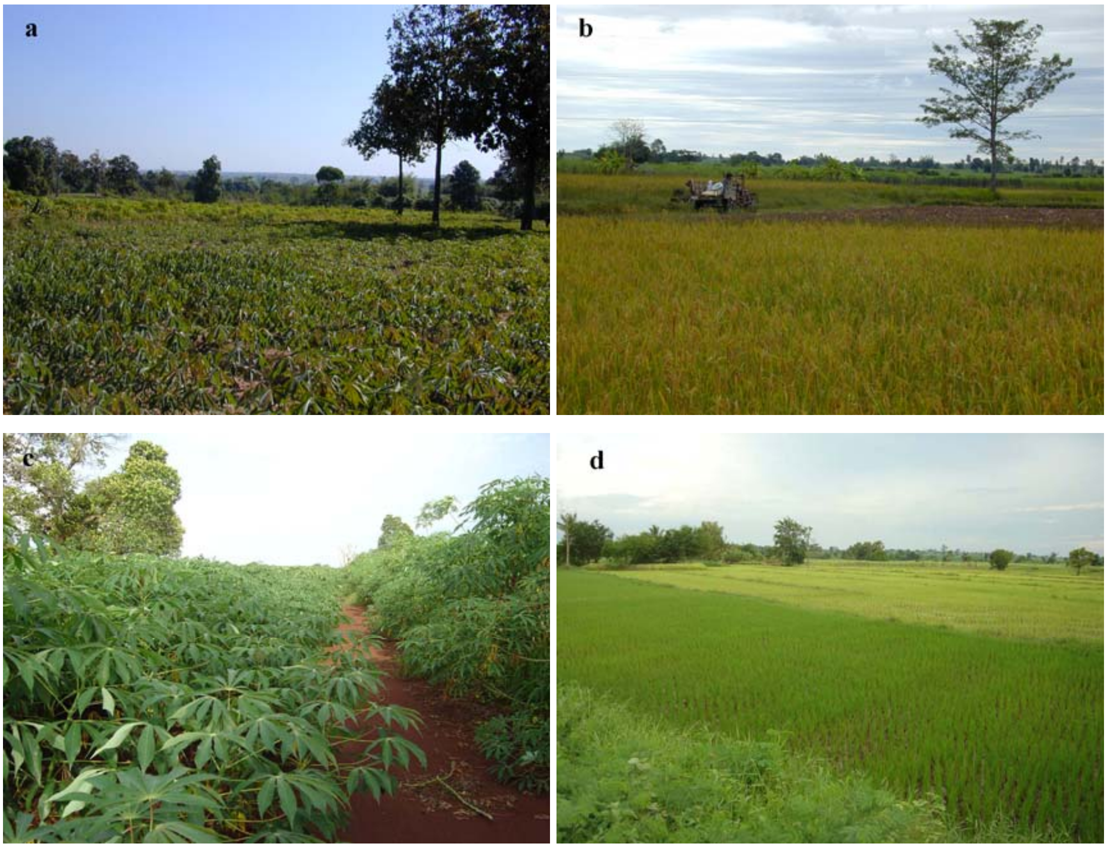


Figure 3 Present land uses of soils on summit, shoulder, midslope and footslope positions (a) the soil on the toeslope position (b) at Nam Phong catena; the soils on the crest, backslope and footslope positions (c), the soil on the valley floor position (d) at Khon Buri catena.

For the Khon Buri catena, four soils were sampled on basaltic lava corrosion undulating plain. This catena transect has a northeast- southwest facing slope and soils have formed on residuum and/ or colluvium derived from basalt. The elevations above mean sea level are 275, 271, 233 and 225 m for the four soils on this catena, on crest, backslope, footslope and valley floor positions respectively. Their coordinates range between 48 0205863^{E} - 48 0203086^{E} and 16 16056^{N} - 16 13349^{N} from the highest position to the lowest position on the catena. The land uses are mainly cassava with some jackfruit, mango, sugarcane and rice (Figures 3c and 3d). The Nam Phong and Khon Buri catenae are under a tropical savannah climate with an average mean annual rainfall of 1,300 mm year^{-1}. The highest daily maximum temperature is 32.7 ^{o}C and the lowest daily temperature is 22.3 ^{o}C. The average temperature is 26 ^{o}C.

Laboratory Methods

Representative profiles at each position on the Nam Phong and Khon Buri catenae were described and sampled by genetic horizon according to standard field study methods (Kheoruenromne, 1999; Soil Survey Division Staff, 1993). Approximately 2 kg of disturbed bulk soil sample from each horizon was air-dried and crushed (but not ground) and the fine earth fraction passed through a 2 mm sieve was used for various chemical, physical and mineralogical analyses. Undisturbed soil samples including core samples and kubiena box samples were collected for some physical and micromorphological analyses respectively. A summary of analytical methods used in this the study is shown in Table 2 and the associated details of each method are summarized in Appendix III.

Table 2 Laboratory methods

Analysis	Method	References
Physical analysis		
1. Particle size analysis	Pipette method	Gee and Bauder, 1986
2. Bulk density	Core method	Blake and Hartge, 1986
3. Water retention	Soil core and pressure plates	Klute, 1986
Chemical analysis		
1. Soil reaction pH	1:1 soil:solution in H_2O and 1 M KCl measured by pH meter	National Soil Survey Center, 1996
2. Organic carbon	Wet digestion and titration by Walkley-Black method	Nelson and Sommers, 1996
Organic matter	Organic carbon concentration × 1.724	
3. Total Nitrogen	Kjeldahl method	Jackson, 1965
4. Extractable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+})	1 M NH_4OAc at pH 7.0 extraction and measured by AAS and flame emission spectrophotometer	Thomas, 1982a
5. Extractable acidity	Barium chloride-triethanolamine solution at pH 8.2	Thomas, 1982b
6. Extractable Al	1 M KCl extraction and titrations with 0.1 M NaOH and 0.1 M HCl	Bertsch and Bloom, 1996
7. Available P	Bray II	Bray and Kurtz, 1945
8. Cation exchange capacity		
- CEC by NH_4OAc	Saturating the exchange site and displacing by 1 M NH_4OAc, at pH 7.0	Chapman, 1965
- CEC by sum of cations	Sum of extractable bases plus extractable acidity	National Soil Survey Center, 1996
9. Effective cation exchange capacity (ECEC)	Sum of bases plus Al extracted by 1 M KCl	National Soil Survey Center, 1996
10. Base saturation percentage		
- %BS by sum of cations	The sum of bases extracted by NH_4OAc (pH 7.0), divided by the sum of cations (extractable bases + extractable acidity) and multiplied by 100	National Soil Survey Center, 1996

Table 2 (Continued)

Analysis	Method	References
11. Extractable Fe, Al and Mn	Dithionite-citrate-bicarbonate (DCB) and measured by AAS	Mehra and Jackson, 1960
	Extraction in 0.2 M ammonium oxalate pH 3.0) and measured by AAS	McKeague and Day, 1966
	Extraction in 0.1 M sodium pyrophosphate pH 10.0) and measured by AAS	McKeague, 1967
12. Total analysis of major and minor elements	Pressed pellets with X-ray fluorescence spectrometer (XRF) using a Philips PW1480 XRF	Karathanasis and Hajek, 1996; Norrish and Chappell, 1977
13. Trace elements content	Aqua regia digestion and measured by ICP-MS using a Perkin Elmer Elan 6000	Lynch, 1999; Soltanpour *et al.*, 1996
Mineralogical analysis		
1. Major and minor minerals of the clay fraction	Oriented clay X-ray diffraction (XRD) analysis using a Philips PW-3020 diffractometer with a graphite diffracted beam monochromator (CuKα 50 KV, 20 mA)	Whittig and Allardice, 1986; Brown and Brindley, 1980)
Micromorphological analysis		
1. Mineral composition and micromorphological features	Polarizing microscope technique	Brewer, 1964; Bullock *et al.*, 1985; Fitzpatrick, 1993
2. Chemical composition of the micromorphological features	Backscattered electron image and elemental mapping by scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) by microprobe analyser (EMPA) on a JEOL 6400 SEM	White and Dixon, 1995
Fine sand grain analysis		
1. Shape and size	Scanning electron microscopy (SEM) on a JEOL 6400 SEM	Doornkamp and Ksinsley, 1973

RESULTS AND DISCUSSION

The whole data set including morphological description, physical, chemical and mineralogical data of the soils are given in the Appendix.

Soil Classification

The soils on both catenae are classified based on their morphology, physical and chemical properties and mineralogical characteristics according to procedure described in Soil Taxonomy (Soil Survey Staff, 1999)

The soils on Nam Phong catena can be classed into two orders; Ultisols, and Alfisols. All soils have clay accumulations in the subsoil justified as an argillic horizon even though soils on the midlsope and footslope positions show little clay accumulation with depth. The soil on the summit has base saturation of less than 35%, it is classified as an Ultisol while soils on the other positions have base saturation of more than 35%, they are Alfisols. Most of soils have ustic soil moisture regime except the toeslope soil. So their suborders are Ustult for the soil on the summit and Ustalfs for the soils on shoulder midslope and footslope positions. The soil on the toeslope position is under aquic condition, so the soil is an Aqualf. With a presence of kandic horizon based on the CEC (by 1M NH_4OAc) of less than 16 cmol kg^{-1} and the ECEC of less than 12 cmol kg^{-1}, the soil on the summit is a Kandiustult. The soil on shoulder has a marked clay accumulation in the subsoil so it is a Paleustalf. The soils on midslope and footslope having have variable clay accumulations with depth, which are Haplustalfs. The soil on the toeslope is an Endoaqualf based on its aquic condition. The soils on shoulder and midslope positions have sandy particle size classes throughout the upper 75 cm of the argillic horizon so they have psammentic subgroup. In addition, the footslope soil is in oxyaquic subgroup since it can be saturated with water in subsurface horizon within 100 cm from the soil surface for 20 or more consecutive days. The soil on the toeslope with a hue of 10YR and the value and chroma more of than 3 within 75 cm from the soil surface has an aeric subgroup. Hence, the soils on the summit, shoulder, midslope, footslope and toeslope positions of this catena are Typic Kandiustult, Psammentic Paleustalf, Psammentic Haplustalfs, Oxyaquic Haplustalf and Aeric Endoaqualf respectively.

For Khon Buri catena, the soil on the crest has an oxic and kandic horizon, ustic moisture regime and a hue of 10R throughout its B-horizon, it is a Rhodic Kandiustox. Soil on backlsope and footslope positions show clay films on ped faces and pore walls in its B-horizon and accumulation of clay with depth which meets a criterion of an argillic horizon. The base saturation is less than 35% for the subsoil horizons. They are classified as Ultisols. They also have an ustic soil moisture regime to be placed in Ustults. The backslope soil has a kandic horizon, therefore, it is Typic Kandiustult. However, the kanic horizon of the Rhodic Kandiustox has lower base saturation percentage than that of the a Typic Kandiustult. Soil on the foootslope position has a plinthic horizon, hence, it is a Typic Plinthustult. The soil on the valley floor position has large cracks on the surface, common slickensides throughout its B-horizon and 30 percent clay or more between the soil surface and a depth of 18 cm. Their features and properties meet criteria of a Vertisol. It has aquic moisture soil regime and its water saturated condition meets a criteria of a Typic Endoaquert. Therefore the soils on crest, backslope, footslope and valley floor position of this catena are Rhodic Kandiustox, Typic Kandiustult, Typic Plinthustult and Typic Endoaquert respectively.

Morphology of Soils on Nam Phong and Khon Buri Catenae

The full soil field morphological description for the Nam Phong and Khon Buri catenae are given in Appendix II. The summary of the field morphological characteristics of soils along Nam Phong and Khon Buri catenae are given in Table 3. This chapter describes dominant soil morphological feature on both catenae (Figures 4 and 5).

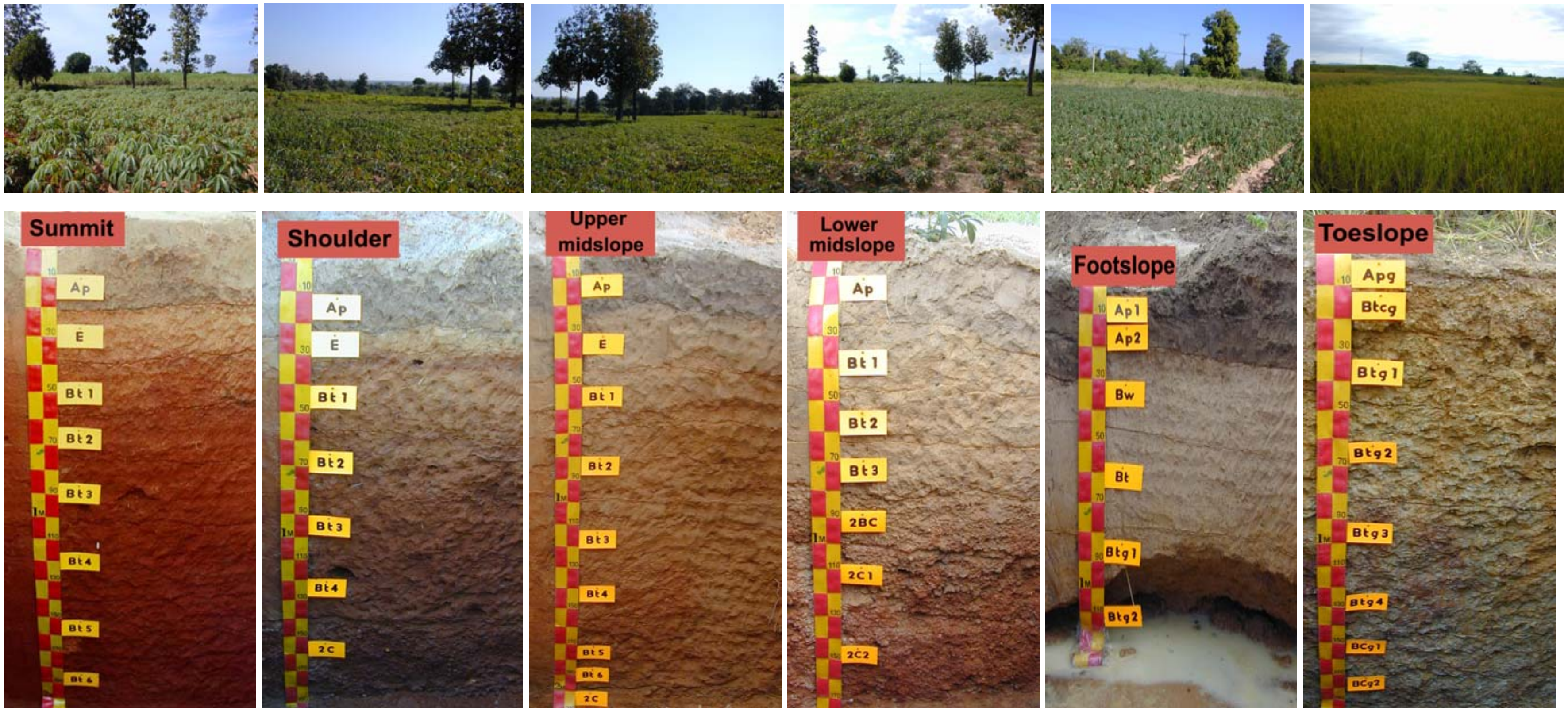


Figure 4 Soil profiles on at Nam Phong catena.

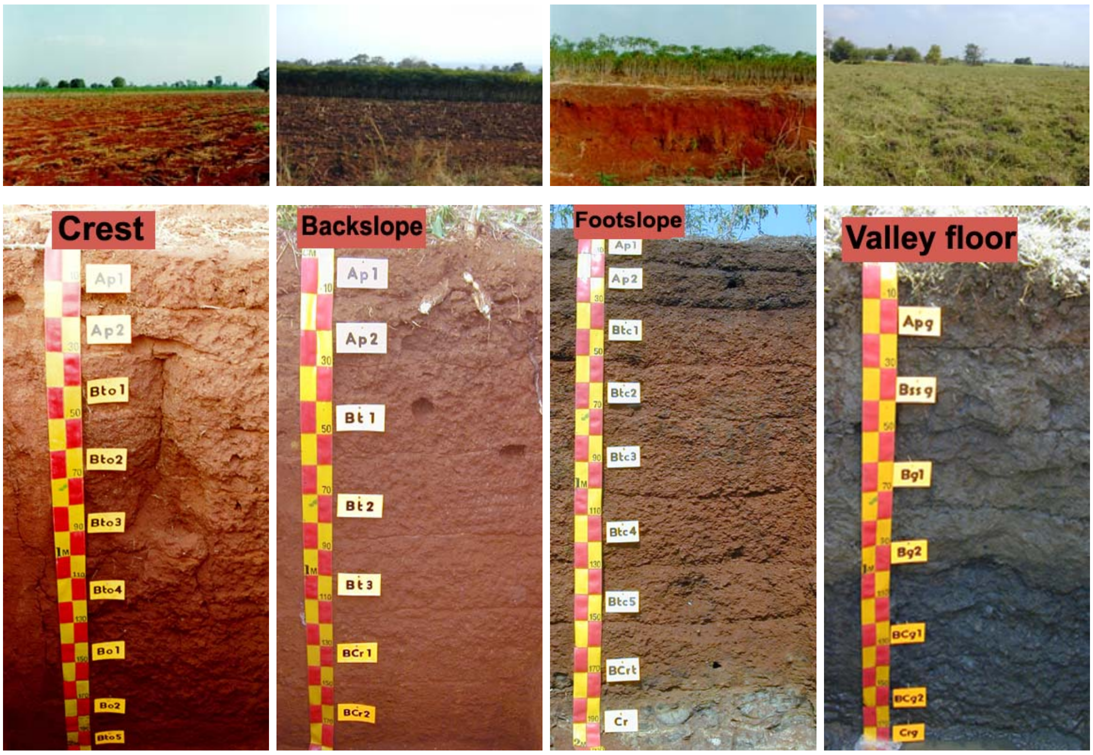


Figure 5 Soil profiles on Khon Buri catena.

1. Soil Profile Development

All soils on the Nam Phong catena are deep. The profile development features are Ap-E-Bt, Ap-E-Bt-2C, Ap-Bt-2C, Ap-Bt-2BC-2C, Ap-Bw-Bt and Apg-Btg-BCg for the soils on summit, shoulder, upper midslope, lower midslope, footslope and toeslope positions respectively (Figure 4). The clay coats on ped facesand pore walls in all soils are evident in the field. The thickness of the E-horizon in the soils decreases from the summit to the lower midslope. This is interpreted that soil on the summit is the highest weathered soil on this catena. Discontinuity of parent materials can be recognized in the soils on shoulder and midslope positions.

The soil profile features on the Khon Buri catena are Ap-Bto-Bo, Ap-Bt-BCr, Ap-Btc-BCrt-Crt and Apg-Bssg-Bg-BCg-Crg for the soils on crest, backslope, footslope and valley floor positions, respectively (Figure 5). The accumulation of the clay throughout the profiles of soils on the backslope and footslope are well observed in the field. A small amount of clay accumulation can be observed on crest soil. However, clay ball and clay coats on pore walls and ped faces can be seen in soils on the crest, backslope and footslope positions. For soil on the valley floor position, crack is well expressed in both the surface and in the lower part of the profile. Also, slickensides and/or pressure faces are common in this soil. Many nodules can be found throughout the soil profile on the footslope position whereas few nodules are present in the lower subsoil on the backslope position. The presence of nodules in soils indicates the wetting and drying periods in their pedogenesis (Acquaye *et al.*, 1992). The small basalt rock fragments are commonly present in some horizons of soils in all positions. In addition, the weathered basalt bedrock is present in the deepest horizon of the soils on backslope and footslope positions. These indicate that all soils on this catena are formed from the basalt.

2. Soil Texture

For Nam Phong catena, soils on the summit, shoulder, midslope and footslope positions are high in sand, low in silt and clay content whereas soils on the toeslope position are high in silt and clay but very low in sand contents. There is an accumulation of clay in all soil profiles. The accumulation of clay in the B-horizon of soils on summit, shoulder and toeslope positions can be clearly observed. Very few of this feature can be observed in soils on the midslope and footslope positions. A presence of sandstone rock fragments on the surface of the soil on toeslope position is interpreted as result of gravitational transfer the upper slope. The textures of soils on the summit, shoulder, midslope and footslope positions are sandy to loamy sand whereas the texture of the soil on toeslope position is sandy loam to silty clay loam. There is a marked difference of textures between the soils on high position and those on the low positions. This indicates that the summit, shoulder, midslope and footslope soils developed on the transported materials derived from sandstone that is confirmed by their micromorphological characteristics. The soil on the toeslope position is believed to form on the residuum of the finer grained sedimentary rock i.e. shale.

All soils on Khon Buri catena have clayey texture as influenced by their parent materials. In the field, the clay accumulation in the B-horizon can be clearly observed

Table 3 Field morphology, particle size distribution, pH and soil features for the Nam Phong and Khon Buri catenae

Horizon	Depth (cm)	Color (moist)		Field pH	Particle size distribution (%)			Structure[1/]	Other
		Matrix	Mottle		Sand	Silt	Clay		
	Nam Phong catena								
		Summit: Typic Kandiustult, sandy, kaolinitic, isohyperthermic							
0-20	Ap	7.5YR5/4	-	6.3	85.05	10.40	4.55	12fmsbk	-
20-40	E	5YR6/8	-	6.4	83.02	11.42	5.56	12fmsbk	Few faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls
40-205+	Bt	2.5YR4/8	-	5.0	70.71	10.09	19.20	2fmsbk	Common few faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls
		Shoulder: Typic Kandiustalf, sandy, siliceous, isohyperthermic							
0-23	Ap	10YR5/4	-	6.6	83.17	11.76	5.07	12fmsbk	-
23-35	E	7.5YR6/6	-	6.9	80.36	14.09	5.55	2fmsbk	-
35-140	Bt	7.5YR6/6	-	5.1	72.45	12.98	14.57	2fmsbk	Common distinct faint clay bridges among sand grains and common prominent clay coats on ped faces and pore walls
140-190+	2C	2.5YR4/6	-	5.0	54.00	15.90	30.10	3fmsbk	Few distinct faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls
		Upper midslope: Typic Haplustalf, sandy, siliceous, isohyperthermic							
0-30	Ap	10YR4/3	-	6.0	90.91	6.06	3.03	1fmsbk	-
30-45	E	10YR5/4	-	6.3	88.80	8.70	2.50	1fmsbk	-
45-198	Bt	7.5YR6/6	-	5.9	85.53	9.55	4.92	1fm3fmsbk	Few distinct faint clay bridges among sand grains and clay coats on pore walls
198-210+	2C	7.5YR7/6	-	5.3	67.80	10.10	22.10	2fmsbk	Few distinct faint clay bridges among sand grains and clay coats on pore walls
		Lower midslope: Typic Haplustalf, sandy, siliceous, isohyperthermic							
0-35	Ap	10YR5/3	-	4.8	91.40	6.10	2.50	12fmsbk	-
35-80	Bt	10YR6/6	-	5.2	87.23	8.93	3.83	1fmsbk	Very few faint clay bridges among sand grains
80-100	2BC	7.5YR6/6	-	5.0	87.00	7.50	5.50	1fmsbk	-
100-180+	2C	2.5YR4/8	-	4.9	67.95	7.75	24.30	m	Common faint clay coats on pore walls
		Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic							
0-30	Ap	10YR4/2	-	5.3	89.45	9.30	1.25	12fmsbk	-
30-45	Bw	10YR7/3	-	5.4	89.40	10.10	0.50	1fmsbk	-
45-130+	Bt	7.5YR7/4	-	5.5	88.43	10.40	1.17	1fmsbk	Few faint clay bridges among sand grains and clay coats on pore walls
		Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic							
0-5	Apg	10YR5/3	2.5Y7/2	6.0	72.30	19.10	8.60	3fmse-abk	-
5-30	Btcg	10YR6/4	2.5YR4/6 2.5Y8/1	7.0	40.10	24.50	35.40	3fmsbk	Few faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls
30-143	Btg	2.5Y6/6	2.5Y7/2	8.9	22.80	37.15	40.05	1cabk; se-abk	Common distinct clay coats on pore walls and ped faces
143-195+	BCg	5Y7/1	10YR5/8	9.1	6.80	47.20	46.00	1cabk; se-abk	Few faint clay coats on pore walls and ped faces

Table 3 (Continued)

Horizon	Depth	Color (moist)		Field pH	Particle size distribution (%)			Structure[1/]	Others
		Matrix	Mottle		Sand	Silt	Clay		
	Khon Buri catena								
		Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic							
0-30	Ap	10R3/3	-	4.0	10.63	23.98	65.40	2fmsbk-3fg	Many roots, common clay balls, few rock fragments
30-130	Bto	10R3/3	-	4.5	8.05	8.43	83.52	3mcabk	Many roots, few clay balls, few rock fragments
130-185+	Bo	10R3/3	-	4.5	7.10	7.31	85.60	2fmsbk-cg	Few roots, common clay balls, very few rock fragments
		Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic							
0–30	Ap	5YR3/3	-	6.5	24.30	22.11	53.60	2fmsbk-3fg	Common tuberrus roots, few clay balls, common rock fragments
30-119	Bt	2.5YR4/6	-	5.5	13.81	11.52	74.67	3fmabk	Few roots, few clay balls, few crack, few rock fragments
119-180+	BCr	2.5YR4/6	-	5.5	18.82	15.18	66.00	2fmse-abk	Very few roots, common clay balls, many rock fragments and gravel, traces of ant's nest
		Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic							
0–30	Ap	5YR3/3	-	6.5	49.06	17.55	33.40	1mcsbk	Many roots, few clay balls, many gravels
30-150	Btc	2.5YR3/6	-	4.5	20.68	11.24	68.08	2mcsbk	Common roots, few clay balls, many gravels
150-180	BCrt	5YR3/4	-	4.0	19.90	17.70	62.40	1,2mcsbk	Few roots, common clay balls, many gravels
180-197+	Cr	2.5Y6/1-6/2	-	6.5	-	-	-	-	Basalt texture
		Valley floor: Typic Endoaquert, very-fine, smectitic, isohyperthermic							
0-25	Apg	10YR3/2	10YR5/6, 5YR4/6, 2.5Y4/4, 2.5Y3/3, 5Y7/8	7.5	14.34	26.46	59.20	2fmsbk	Many roots, few rock fragments, few pressure faces
25-50	Bssg	2.5Y3/1		8.0	5.60	22.40	72.00	1cabk-se-m	Few roots, few clay balls, common pressure faces, common slickenside
50-110	Bg	2.5Y4/1		8.0	5.48	16.93	77.60	2fmsbk	Very few roots, common clay balls, common slickenside, few pressure faces, few rock fragments
110-160	BCg	Mixed 10Y3/1, 5Y3/2		8.0	13.08	17.13	69.80	1cabk-r	Very few roots, few clay balls, few slickenside, few pressure faces, few rock fragments
160-180+	Crg	Mixed 2.5Y3/1, 10GY3/2		8.0	18.76	29.64	51.60	1fmabk-r	No roots, few pressure faces, few variegated sand and rock fragments

[1/] 1 = weak, 2= moderate, 3 = strong;
f = fine, m = medium, c = coarse;
abk = angular blocky structure, sbk =subangular blocky structure, se-abk= semi-angular blocky structure, m = massive, g = granular structure, R = rock structure

in soils on the high position. Nevertheless, the soil on the valley floor does not show the clay accumulation with depth. This is possible due to its saturation by water throughout the profile retarding clay translocation (Buol *et al.,* 2003).

3. Soil Color

Colors of surface soils on Nam Phong catena are quite similar as brown (7.5YR-10YR), but the subsurface horizons are red (2.5YR) on the summit position and gradually changing to light gray (5Y) on the toeslope position. The dark color of the surface soil reflects the high organic mater content. In addition, the soil on the toeslope position is flooded in some seasons inducing the release of iron and manganese from the secondary mineral (Buol *et al.*, 1997) as indicated by the presence of the brownish yellow and dark brown mottles.

The changes of colors in soils on Khon Buri catena are obvious. In the soils on crest, backslope and footslope positions, the dark red (10R, 2.5YR) color prevails. Then change to the gray (10Y) color in the valley floor soil is abrupt. The color of the surface soil is darker than those of the subsurface horizon reflects the higher organic mater content in the surface soil. The olive brown, dark olive gray and yellow mottles are present throughout the soil profile on valley floor position. The soil on the valley floor has the most shallow water table with some seasonal fluctuation. Secondary minerals release iron and manganese, further induce a presence of mottles in this soil (Buol *et al.*, 1997).

4. Soil Drainage Condition

For Nam Phong catena, soils on the summit, shoulder and midslope positions are well drained, footslope soil is moderately well drained and the soil on the lowest position on the toeslope is poorly drained. For Khon Buri catena, soils on the crest, backslope and footslope positions are well-drained and lacking redoximorphic features. The soil on the valley floor position is poorly drained (Soil Survey Division Staff, 1993).

Generally, the movement and distribution of water on slope is one of the primary reasons for soil differences on landscape (Hall, 1983; Gerrard, 1992) as observed in soils along both catena transects. The differences in drainage are responsible for the gradual color changes that are frequently seen in catena (Gerrard, 1992). Upslope soils of both catenae are moderately well-drained to well-drained whereas the soils on the lowest position of both catenae are poorly drained. The red color of soil on the summit position shows the presence of non-hydrated iron oxide in the soil. The iron is well dispersed and usually partly attached to the clay fraction thus the clay itself appears red. On middle and lower parts of the slope, drainage is slower, partly because of the moisture seeping downslope from the upper soil. These soils remain moist longer and dry out less frequently and less completely. This leads to an increasing degree of hydration of iron. The red color then changes to a brown or yellow. The hydrated iron oxides are mainly limonite and goethite. On the lowest position on the catena where drainage can be very poor and where part or all of the soil profile is waterlogged, the reduction of iron and other soil compound takes place. Under these conditions, bacteria obtain their oxygen from the oxygen containing compounds and these are then reduced to other compounds. These waterlogged soils are usually bluish-gray, greenish-gray or even neutral gray in color. In the part of the soil profiles where the water table fluctuates mottling is generally produced. The redoximorphic feature is also present only in soil on lowest position of both catenae.

5. Synthesis on Soil Morphology

The summit profile on the Nam Phong catena experiences continuous well drained conditions, hence it is red to dark red in color with no mottles. The red color gradually decreases in intensity downslope along the catena. The toeslope profile is at the lowest position on the soil sequence. It is poorly drained and the soil has a yellow color and many mottles which is consistent with its wet environment. The pH of summit to footslope soils ranges from 4.5-6.5 and is more than 8 for the toeslope profile, which contains both $CaCO_3$ and $MgCO_3$. The soils are deep at all positions on the Nam Phong catena. The thickness of the Ap-horizon increases from the summit to footslope position and it is thinner in the toeslope profile. Their textures range from sandy to loamy sand and sandy to sandy clay loam for the surface soil and the subsoil respectively. Iron and manganese oxide nodules occur at 5-30 cm depth in the toeslope soil due to seasonal redox variations associated with the high water table at this position. In addition, there is an abrupt change in materials from the Bt-horizon to the 2BC or 2C horizon at the shoulder and midslope positions because of a presence of various sized up to 3 cm rock fragments gravels in the 2BC or 2C horizon (i.e. stone line). Hence a discontinuity of soil parent materials can be recognized at shoulder and midslope positions.

All soils on the Khon Buri catena are deep. The accumulation of the clay in subsoil horizons for soils on the crest, backslope and footslope is apparent in the field. The soil on the crest shows the highest degree of weathering and the highest development on this catena confirmed by the presence of granular structure, a dark red color throughout the soil profile and a little evidence of clay translocation within the soil profile. For soil on the valley floor position, cracks are well expressed in both surface and subsurface horizons; slickensides and/or pressure faces are also common. Many iron and manganese oxide nodules occur throughout the soil profile on the footslope position whereas only a few of them are present in the deeper part of the soil on the backslope position indicating the wetting and drying periods that induce pedogenic redox processes (Acquaye *et al.*, 1992). Small fragments of basalt are common in some horizons at all catena positions and weathered basalt bedrock is present in the deepest horizon of the soils on backslope and footslope positions. This evidence indicates that all soils on this catena have formed predominantly from basalt. Changes of soil color within the Khon Buri catena are obvious in the field. In soils on the crest, backslope and footslope positions, a dark red (10R, 2.5YR) color dominates with an abrupt change to a gray (10Y) color for the valley floor soil. Soils on the crest, backslope and footslope positions are well-drained and lacking redoximorphic features. The soil on the valley floor is poorly drained, olive brown, dark olive gray and with yellow mottles which are characteristic features of aquic conditions occurring throughout the profile.

Physical Characteristics of Soils on Nam Phong and Khon Buri Catenae

The full physical data sets of the soils on both catenae are given in the Appendix I, Tables 1-3. This part discusses the bulk density, water characteristic and available water capacity of the soils.

1. Bulk Density

Bulk density values of soils on, summit, shoulder, midslope and footslope on Nam Phong catena range from 1.37-1.55 and 1.34-2.02 Mg m^{-3} for the surface soils and subsurface soil horizons, respectively. The toeslope soil has a high bulk density for both surface soil (1.7 Mg m^{-3}) and subsurface horizons (1.63-1.86 Mg m^{-3}) (Figure 6. Soils on the Khon Buri catena (Figure 6) have bulk density values ranging from 0.84-1.47 Mg m^{-3} and 0.98-1.94 Mg m^{-3} for the surface soils and subsurface horizons, respectively. The high bulk density values in the top soils possibly indicate the impact of mechanized farming practices. Their bulk density of soils slightly increases with depth for both catenae. This can indicate the effect of clay translocation in their profiles (Marshall and Holmes, 1979; Owens and Watson, 1979; Calverts *et al.,* 1980).

Generally, the bulk density has a negative relationship with the soils porosity. Soils on both catenae are highly leached and highly weathered. Subsequently, the eluviation and illuviation processes induce clay accumulation in the soil profile. The fine material acts as the cementing agent among the coarse materials. Hence, the bulk density is high whereas the soil porosity is low in the deeper horizons. In addition, the bulk density of these soils tends to increase downslope for both catenae. This is possibly caused by the movement of fine material from the upper slope to the lower positions (Moniz and Buol, 1982). However, the bulk density does not change significantly along both catena transects implying that the rate of mass movement downslope is fairly slow (Litaor, 1992).

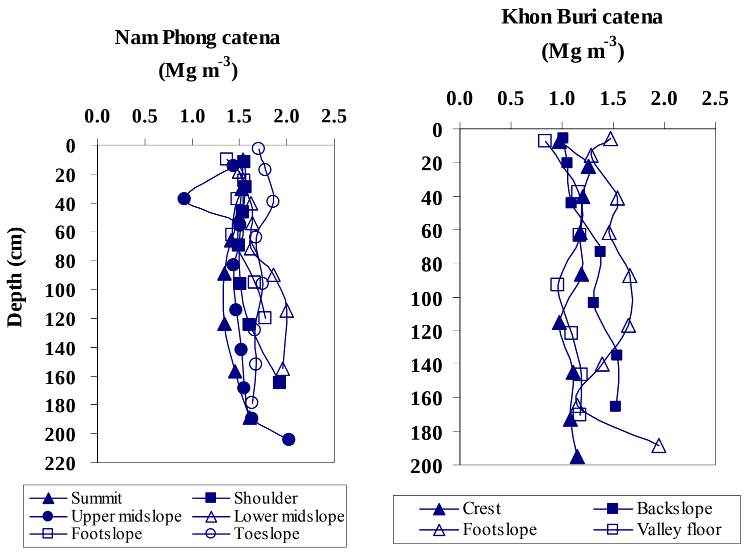
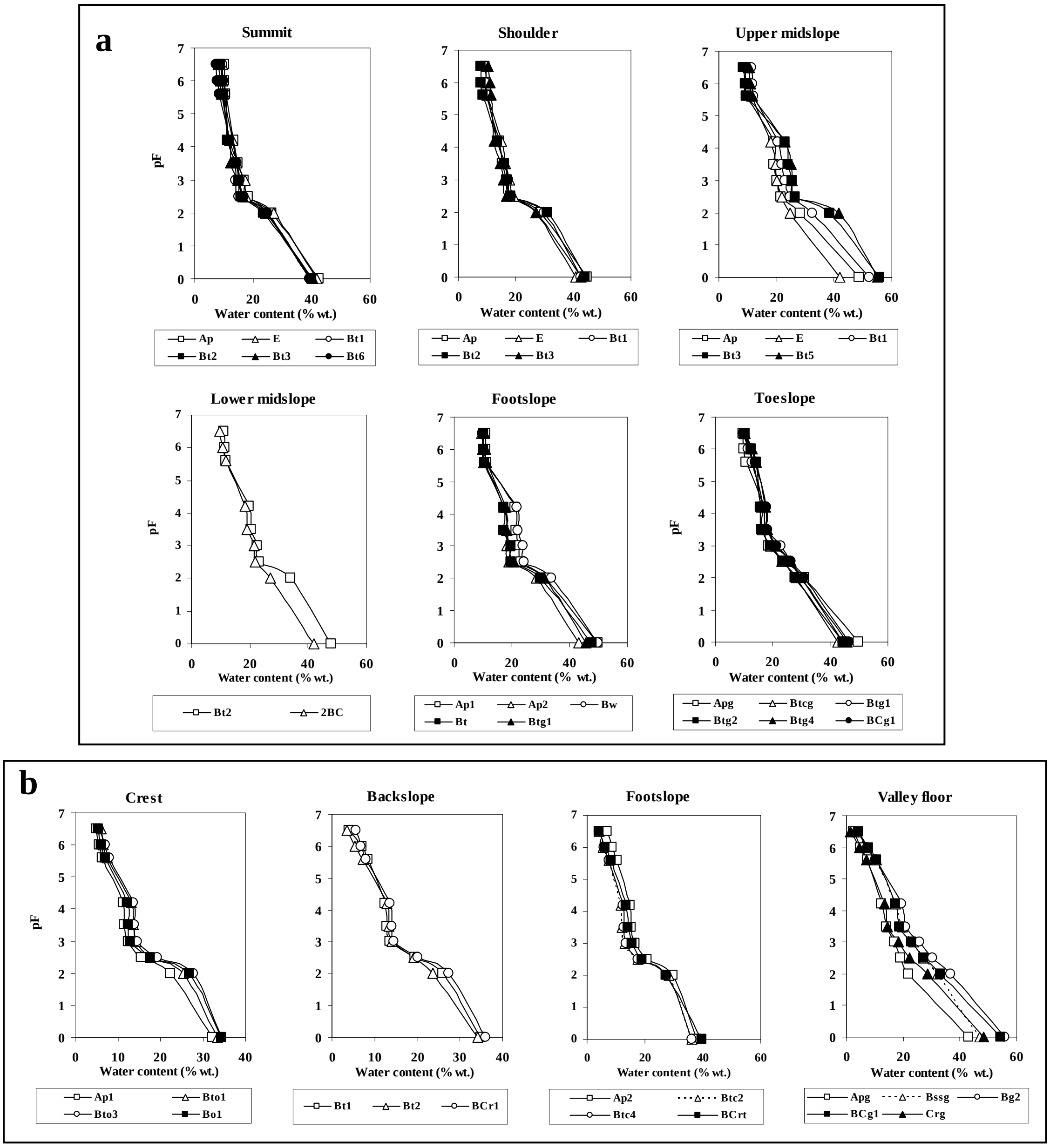


Figure 6 Depth function of the bulk density for soils on the Nam Phong and Khon Buri catenae.

2. Soil Water Characteristic

Figure 7 shows the water retention curves for soils on Nam Phong and Khon Buri catenae indicating the relationships between the soil moisture and the matric potential (pF).

The water retention curves of the upslope soils on both catenae can be divided into three parts. For the first stage, the water content in soils much decreases when the matric potential changes 2 units from pF 0 to 2 where the water content approximately changes 20-30 percent by weight. In the second stage, the matric potential changes only 0.5 units (pF 2.0 to pF 2.5) when the water content in soils decreases approximately 10 percent by weight. For the last stage, the water content only slightly changes at a high matric potential. In the soils on the lower position, two parts in the water retention curves can be identified. At low pF the matric potential changes 2 units (from pF 0 to 2) the water content in soil much decreases while the at high pF (>2.0) the water content in soil only slightly changes.



<u>Figure 7</u> Water retention curves of the soils on the Nam Phong catena (a) and Khon Buri catena (b).

Upslope soils on both catenae, lose water quickly at the low matric potential (pF 0-2) but at the pF higher than 3, the water content in soils slightly decreases. This indicates that the water retention in these soils is mostly in the macro-pores, where soils can have insufficient water in some drought periods of growing season.

The toeslope and valley floor soil, condition is different and the decrease of soil water is slow at higher pF. This can be due to their higher clay content. So the water content retained in the macro-pore is quite equal to that in the meso- and micro- pores which make them suited for paddy cultivation (Marshall and Holmes, 1979; Hillet, 1982; Brady and Weil, 1999).

3. Available Water Capacity

The pF 2 and 4.2 have usually been considered representatives of field capacity and permanent wilting point respectively. In this study, the difference of those two values is an estimated of available water capacity (Figure 8).

For soils on the higher part of the Nam Phong catena, the available water capacity of the surface soil ranges from 2.76 to 7.51 %wt. while those of the subsurface horizons are from 2.53-11.64 %wt. The soil on the toeslope position has the highest available water capacity value whereas soils on the midslope have the lowest available water capacity. For Khon Buri catena, the available water capacity of surface soil and subsurface horizons ranges from 8.13-12.80 and 8.55-15.32 %wt. respectively. Crest soil shows the lowest available water capacity while the soil on the valley floor position has the highest available water capacity.

The sequence of soils based on the highest to the lowest values of their available water capacity for Nam Phong catena are soils on the toeslope, summit, shoulder, midslope and footslope position. For the Khon Buri catena, soils on the valley floor, backslope, footslope and crest positions show the sequence of available water capacity from the highest to the lowest.

4. Synthesis

The upslope soils have a lower bulk density than those on the lowest position of both catenae which are possibly due to the fine material that moves down to the lower positions on the landscape. A trend of this bulk density is quite constant throughout soil profiles with a slight increase with depth for all soils from both catenae. This is common for tropical soils (Sanchez, 1976; Young, 1976), indicating translocation and accumulation of clay in the profile. However, the upslope soils on

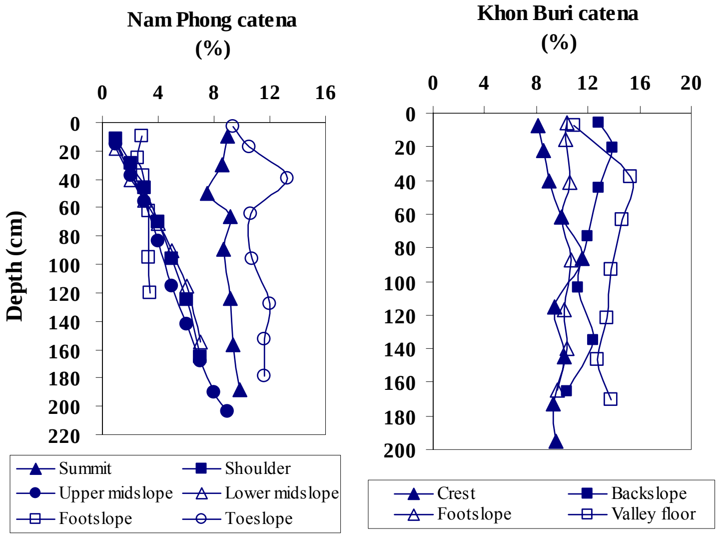


Figure 8 Depth function of available water capacity in soils for the Nam Phong and Khon Buri catenae.

Nam Phong catena have a higher bulk density than those upslope soils on the Khon Buri catena. This is possibly due to the nature of structure reflecting higher porosity in soils on Khon Buri catena (Nune *et al.*, 2000; Schaefer, 2001; Tawornprek, 2005; Trakoonyingcharoen, 2005). Available water for plant growth can be explained by water retention curves (MaClean and Yager, 1972; Marshall and Holmes, 1979). For the upland soils of both catenae, most of water is stored in macropore at pF below 2.5. In contrast, more available water exists in soils on the lowland areas of both sites as the water well distributes in various sizes of pores.

Soil Chemical Properties Change along Nam Phong and Khon Bueri Catenae

The chemical characteristic data of soils on the Nam Phong and Khon Buri catenae are given in Appendix I, Tables 4-8. The factor analysis was employed to identify the chemical property trends within and between profile horizons for both catenae with an emphasis on the spatial difference of soil chemical properties on landscape.

1. General Soil Chemical Properties on Nam Phong Catena

Depth functions of chemical properties of soils on Nam Phong catena are summarized in Figure 9. The soils at all positions on catena have the highest organic matter content in the surface which decreases uniformly with depth in the profile (Figure 9b). The differences in the amount of organic matter are probably due to the differences of plant production and litter decomposition rate both of which are affected by soil moisture content (Sanchez, 1976; Brady and Weil, 1999). Total N, available P and K are high only in the top soil and much decreasing with depth somewhat depending on the organic matter content except for the toeslope soil (Figures 9b, 9c and 9d). These indicate that organic matter is the main source of nitrogen in soils and it also release available phosphorus (Thompson, 1978; Mengel and Kirkby, 1987). The very high available P and available K in the deeper horizons of the soil on the toeslope reflect the influence of fine grained sedimentary parent rock material (Mutscher, 1985; Phetchawee *et al.,* 1985).

The soils on the summit to the footslope positions are acidic but the soil on the toeslope is alkaline (Figure 9a). This alkalinity is associated with the high extractable bases, especially Ca and the presence of $CaCO_3$ nodules. The low content of extractable K in soils at all positions can be due to the low potassium in their parent rock and potassium can leach away easily (Figure 9h) (Brady and Weil, 1999). The low pH values of the soil on high position indicate acid weathering and basic cation leaching as the important pedogenic processes, while the high pH values of those on the lowest position are attributed to a lower intensity of weathering and leaching. The large difference in CEC between soils in upslope positions and that on the toeslope is due to the greater clay content of the toeslope soil which may be due to *in situ* formation of clay and possibly to a difference in parent material (Figure 9j).

Trend of extractable Al is quite uniform with depth (Figure 9k) except that in the summit soil which increasing with depth indicating the highly weathered and highly leached conditions. Extractable Al cannot be detected in the deeper horizons of soil on the toeslope position. This is possibly due to the high pH inhibiting Al

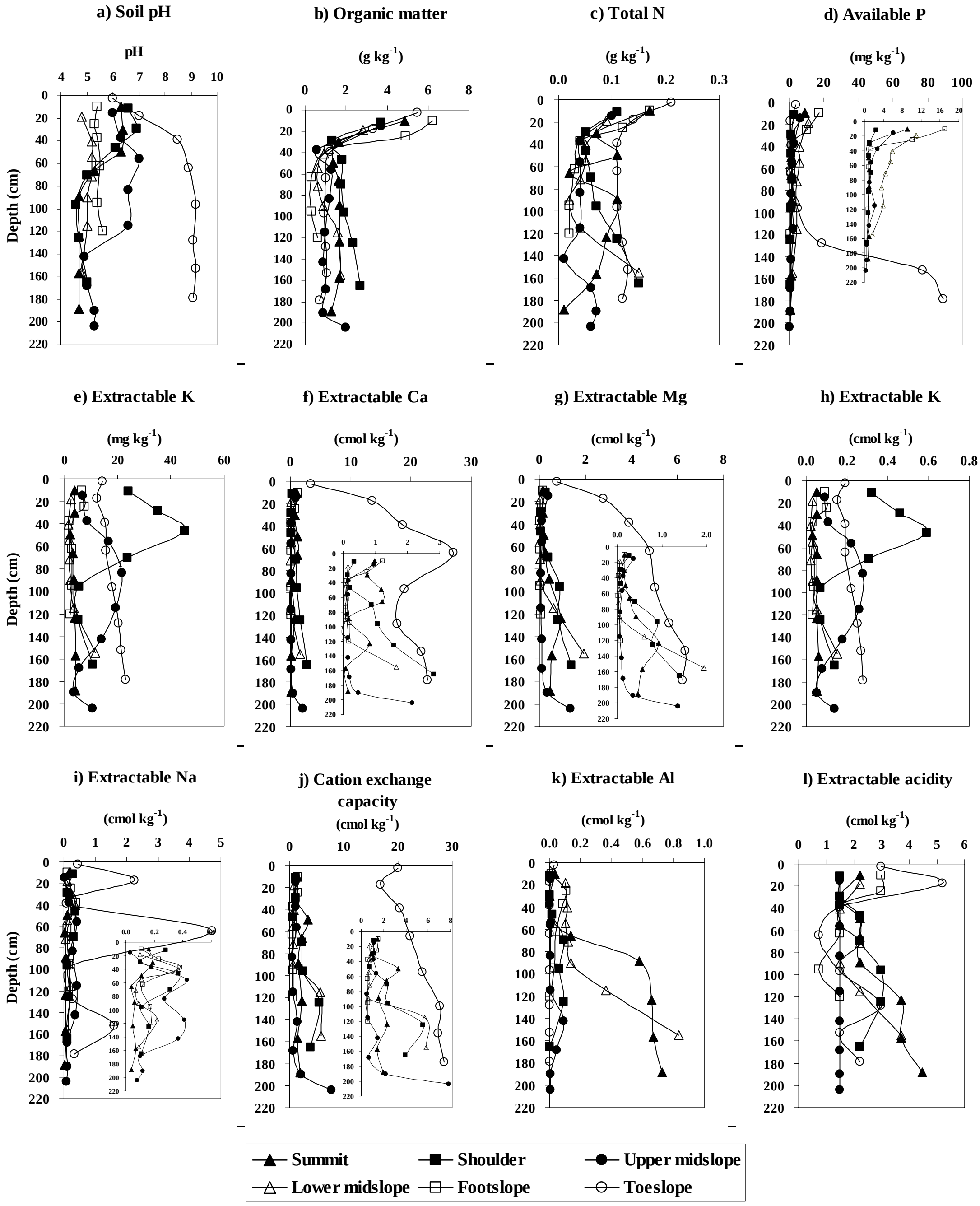


Figure 9 Depth functions of some chemical properties of soils on Nam Phong catena.

release into the soil solution (Sanchez, 1976; Buol *et al.*, 1997). The constant trend of extractable acidity with depth (Figure 8l) can partially due to the low organic matter content of the soil (Thomson and Troeh, 1978).

2. General Chemical Properties for Khon Buri Catena

For Khon Buri catena (Figure 10), all soils show the general trend of having the highest organic matter content in the surface soil (Figure 10b). Most of soils on Khon Buri catena have high available P only in the surface soil and it decreases markedly with depth (Figure 10d) possibly due to the residual effect from the fertilizer applied. This can also reflect the higher leached condition where soluble Fe and Al in the soil can fix phosphorus (Landon, 1991).

The pH of soils on the crest is uniform with depth (Figure 10a). For backslope and footslope soils, pH decreases with depth and for soil on the valley floor pH increases with depth. The low pH values of the soils at higher positions on the catena indicate acid weathering and leaching of basic cations as the important pedogenic processes, while the high pH values of soil on the valley floor are attributed to the accumulation of basic elements transported down from upslope. The low ΔpH of soils on high position indicates variable charge due to high iron oxide concentration (Gillman, 1984). In contrast, permanent negative charge prevails in soils on the lower backslope and valley floor positions as reflected by the high ΔpH are higher and the presence of 2:1 clay minerals.

Extractable bases are abundant in the valley floor soil but not in the upslope soils as indicated by their values of percentage base saturation (Figures 10f, g, h and i). The lowest amount of extractable Ca, Mg, Na and K can be detected in the crest soil, as can generally be found in Oxisols (Marques *et al.*, 2004a). The amount of extractable Mg is higher than the other basic cations in this valley floor soil, inducing a condition that favors smectite formation (Weaver *et al.,* 1971; Harder, 1972; Borchardt, 1977; Reid *et al.,* 1996). The CEC values increase downslope and are highest in the soil on the valley floor where smectite is abundant. The lower CEC of the three upslope soils indicates the dominance of kaolin (Figure 10j). The crest soil has the highest extractable Al values indicated the high leaching condition (Figure 10k).

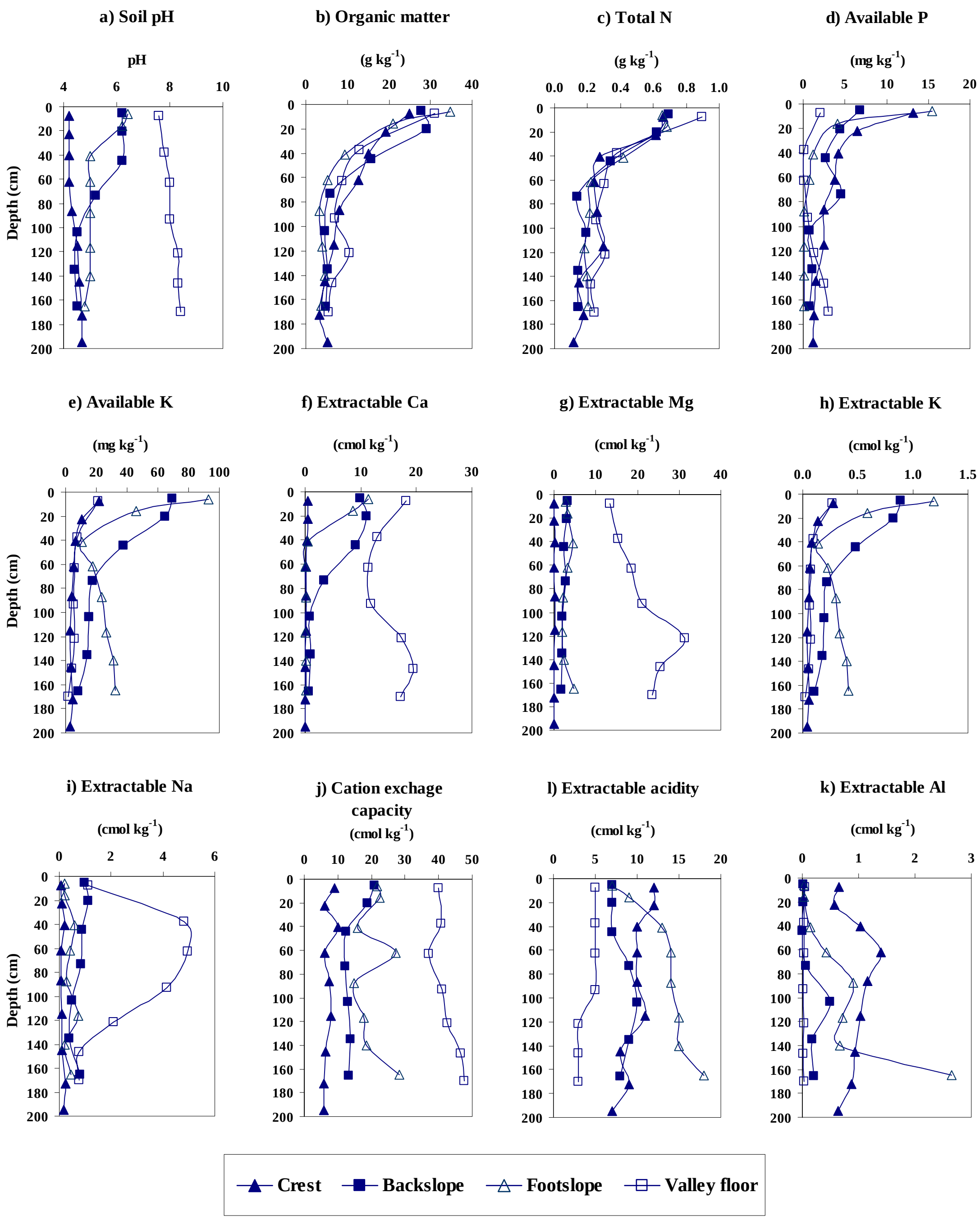


Figure 10 Depth functions of some chemical properties of soils on Khon Buri catena.

3. Forms of Extractable Iron and Aluminum in Soils for the Nam Phong and Khon Buri Catenae

Approximate differentiation on three forms of Fe and Al in soils can be made by selective extraction methods. The dithionite citrate bicarbonate extraction system on total free Fe and Al (Fe_d and Al_d) determines the crystalline, amorphous and organic forms of iron, aluminum and manganese especially hematite and goethite minerals (Mehra and Jackson, 1960; Natural Soil Survey Center, 1996). The acid ammonium oxalate method extracts mainly the amorphous forms of the inorganic Fe and Al (Fe_o and Al_o) (McKeague and Day, 1966; McKeague *et al.*, 1971; Schwertmann, 1973; Hodges and Zelazny, 1980). The sodium pyrophosphate extraction dissolves the fractions of Fe and Al (Fe_p and Al_p) in the forms of organic complex. This procedure does not destroy silicate clay structure, oxide and the structure of the hydroxide of iron and aluminum (McKeague, 1967). However these procedures have proved more successful on differentiating Fe than Al in soil (McKeague *et al.*, 1971). The various forms of Fe, Al and Mn concentrations in soils on both catenae are given in Appendix I, Tables 6 and 7.

3.1 Extractable Fe

In the soils on Nam Phong catena, the Fe_d values decrease downslope (Figure 11) as the red color gradually changes to gray color to the lowest position on the catena (Whitkamp *et al.*, 1996). In general, soils on the upper part of a catena where well-drained condition prevails contain more free iron than do the poorly-drained soils at the base of a catena (Boonsompoppunth, 1984). For this catena most Fe in the toeslope soil is Fe_d indicating that prolonged reducing condition do not occur (Weitkamp *et al.,* 1996). The relative low Fe_o values for all upslope soils indicates that amorphous forms of iron characteristic of seasonally reducing soil environment are minor constituent of these soils (Schwertmann and Taylor, 1989). The high Fe_d in soil on the toeslope position may be at least partly attributed to the influence of the fine-grained sedimentary parent rock (Bhattacharyya *et al.,* 1992). The Fe_p (organic complexed iron) is minor and most abundant in the surface horizons of the profiles where most organic matter occurs. However, the soil on the toeslope position shows the highest Fe_o and Fe_p values, associating with an increasing of organic matter downslope. The organic matter is formed with active iron as an organic iron complex (Schwertmann and Taylor, 1989).

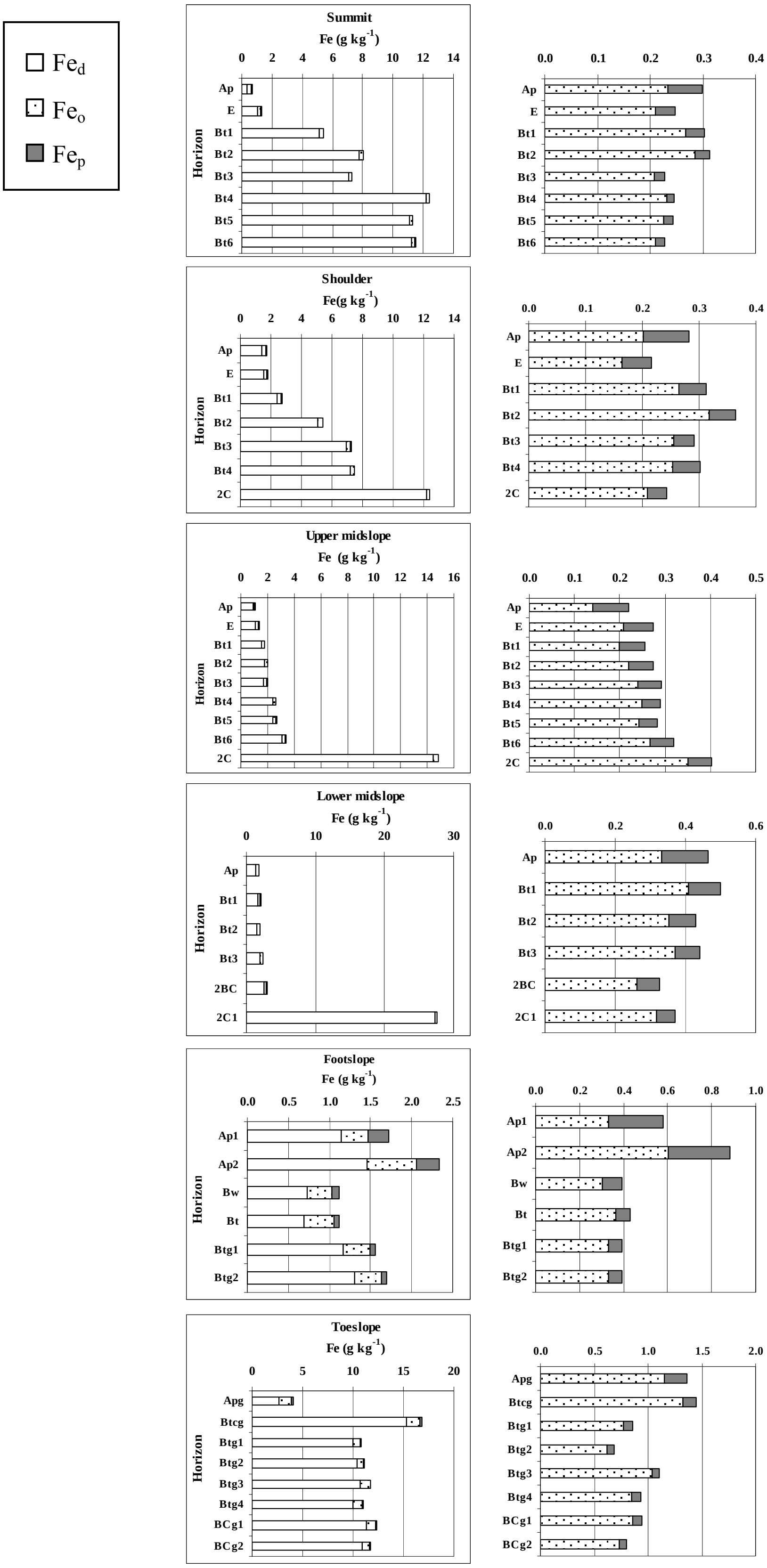


Figure 11 Dithionite citrate bicarbonate, ammonium oxalate and sodium pyrophosphate extracted Fe of soils on Nam Phong catena.

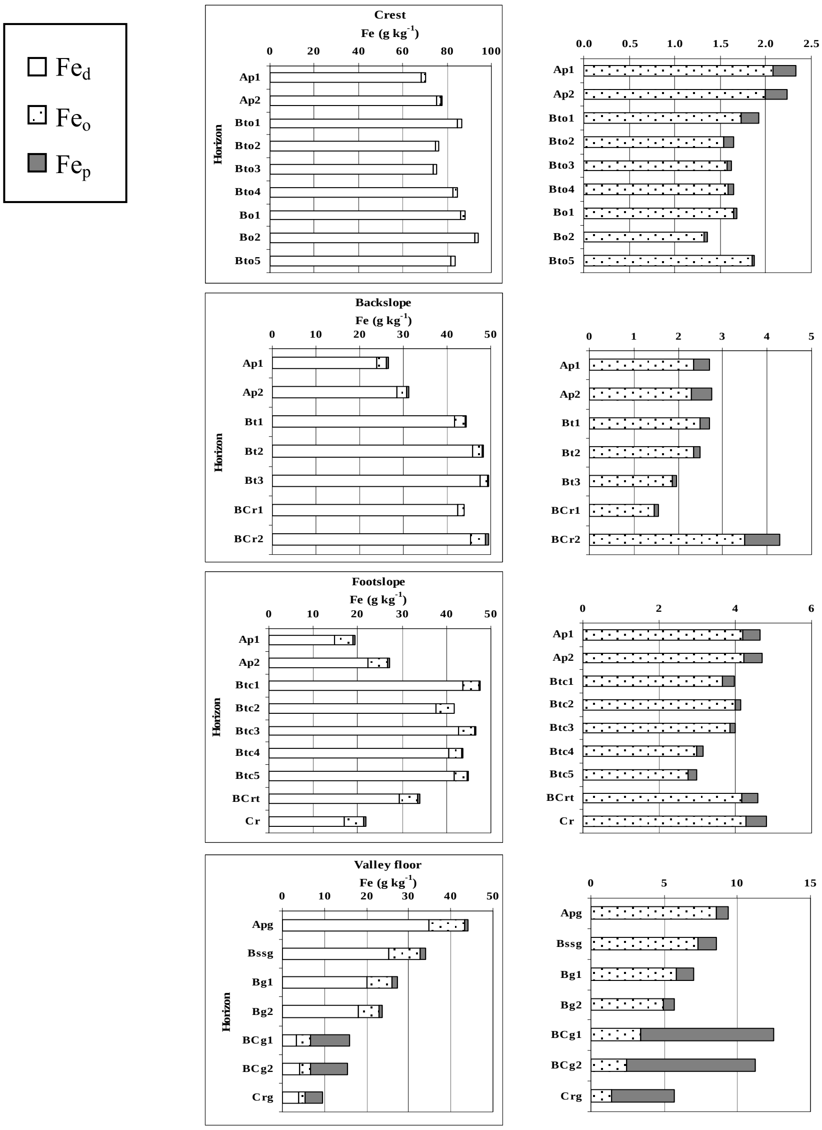


Figure 12 Dithionite citrate bicarbonate, ammonium oxalate and sodium pyrophosphate extracted Fe of soils on Khon Buri catena.

For Khon Buri catena (Figure 12), free iron (Fe$_d$) is highest and the amorphous Fe (Fe$_o$) concentration is lowest in the soil on the crest position. The low concentration of free iron (Fe$_d$) in the valley floor soil reflects the more poorly drained nature of this soil (Ogg and Smith, 1993) due to the periodic reduction and removal of dissolved iron in laterally seeping groundwater (Ojanuga *et al.*, 1976), and also to iron being incorporated into authigenic smectite (Stucki, 1988.).

3.2 Extractable Al

Figures 13 and 14 show the various forms of the extracted Al in soils on Nam Phong and Khon Buri catenae respectively. Soils on the Nam Phong catena shows the Al_d decreasing from the soil on the summit to those on the footslope position and increasing again in the soil on the toeslope position. In the soil on the toeslope, the Btcg-horizon shows the highest Al_d content and the value decreases downwards. For the soils on Khon Buri catena, the soil on the crest shows a relatively higher Al_d content than those of the other soil positions. Comparatively, the Al_d content of the soils on the Khon Buri catena are higher than those on Nam Phong catena, possibly attributed to the influence of their parent materials (Bravard and Righi, 1989; Bowell, 1993).

The Al_o gives an estimate of Al in the allophone, imogolite and organic matter together with minor amounts which may substitute in iron oxide (Child *et al.*, 1983). Anderson *et al.* (1982) used Al_o as an estimate of total translocated Al, although it will also include any of the above types of Al which form *in situ*. The Al_o content of the soils on Nam Phong catena shows a similar trend to that of the Al_d content. Generally the Al_o content should be lower than the Al_d content (McKeague *et al.*, 1971; Arshad *et al.,* 1972; Schwertmann, 1973; Hodges and Zelazny, 1980). In this study, the Al_o content is higher than the Al_d content in some horizons of the soils on Nam Phong catena. Similar to occurrences elsewhere reported by other workers (Litaor, 1992; Mahaney *et al.*, 1994). This may be due to the effect of the pH of the buffer solution (Mahaney *et al.*, 1994). For the soils on the Khon Buri catena, the Al_o content is highest in the soil on the footslope position. This is corresponding to the high goethite content in soil on this position. Norrish and Tylor (1961) proposed that goethite should be recognized as an important source of the often large amount of Al released by this oxalate extraction. The Al_o content of the soils on the valley floor position is the lowest and decreasing with depth corresponding to the decreasing of the organic matter content. This is interpreted as being due to the alkaline condition of valley floor soil.

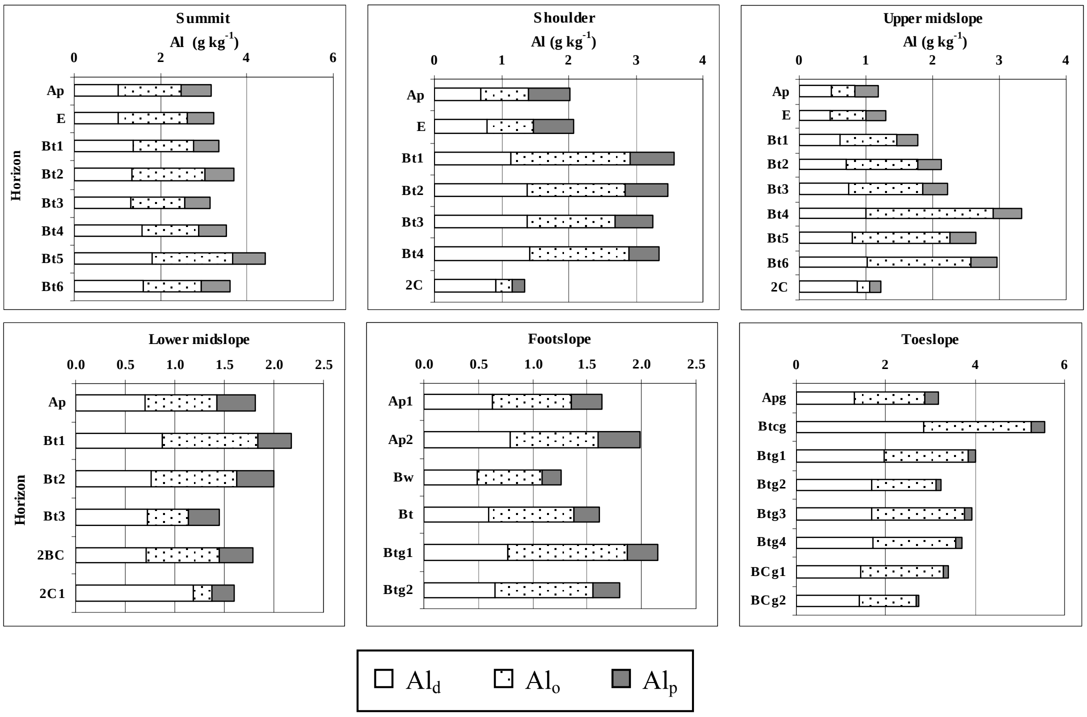


Figure 13 Dithionite citrate bicarbonate, ammonium oxalate and sodium pyrophosphate extracted Al of soils on Nam Phong catena.

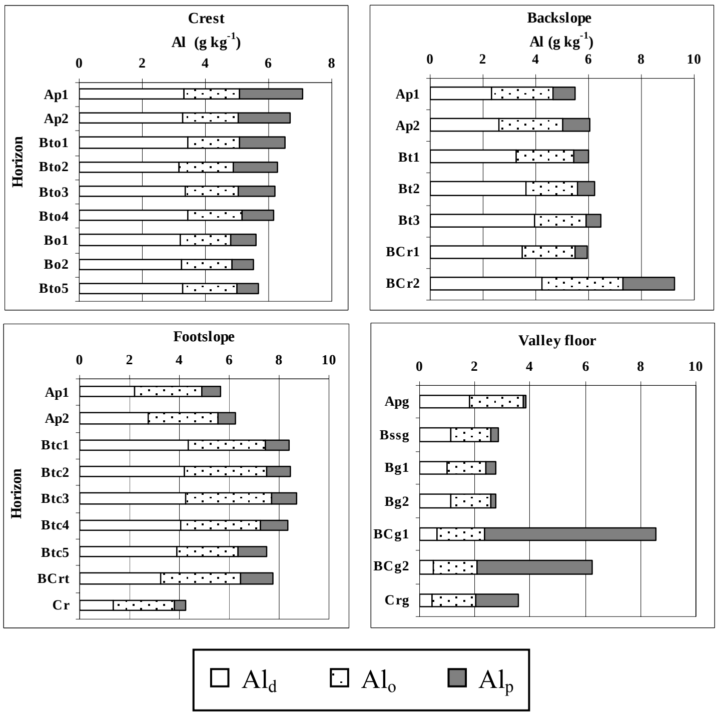


Figure 14 Dithionite citrate bicarbonate, ammonium oxalate and sodium pyrophosphate extracted Al of soils on Khon Buri catena.

The Al_p gives an estimate of the amount of organic-bound Al. The soil on the summit contains the highest amount of Al_p on Nam Phong catena. The Al_p content in soils slightly decreases downslope, contrasting with the increase of organic matter content downslope. However, the Al_p tends to decrease with depth reflecting a decrease of the organic matter content within the soil profiles. Soils on Khon Buri catena, show the similar trend of the Al_p content to those on Nam Phong catena. The soil on the crest has the highest Al_p. The Al_p decreases downslope which is again contrasting with the trend of the organic matter content. The decreasing trend of Al_p with depth in the profile correspond slightly to a decreasing trend of organic matter content.

4. Spatial Differentiation in Chemical Properties of Soil on Catenae

Results of factor analysis on standardized chemical component for Nam Phong and Khon Buri catenae are given in Figure 15.

Two factors explain 66 percent of the variation in the data for Nam Phong catena. The chemical properties can be separated to three main groups and reflecting the difference of soils on landscape as shown in Figure 15. The first group composed of Fe_o/Fe_d, OM, Fe_p, Mn_p and total N. The second group includes Fe_o, Mn_d, Mn_o, CEC, pH H_2O and pH KCl, available P, available K, extractable Na, extractable Ca, extractable Mg, extractable acidity, Mn_d, Mn_o, Al_o, Al_d, Fe_d and clay content. The last group consists of Al_p and extractable Al.

Soils on the summit, shoulder, midslope and footslope positions have quite uniform chemical properties throughout the profile as indicated by the tight grouping of samples in the factor plot and extent to do some overlap. Whereas the soil on toeslope position shows wide diversity in chemical properties which is distinctly different from the soils on the higher positions of the landscape. The toeslope soil is much different from the other soils as based on second group of the chemical properties.

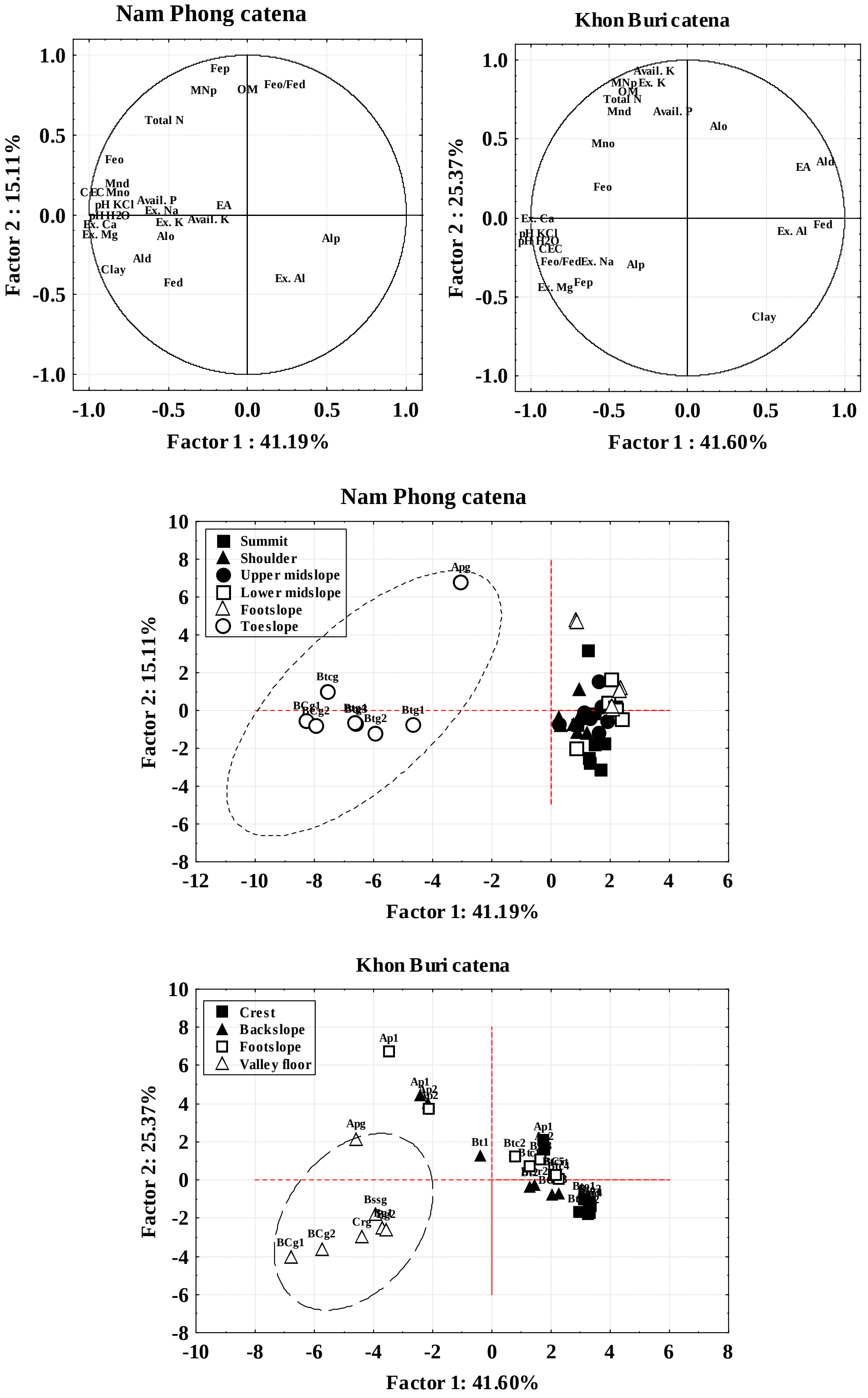


Figure 15 Factor analysis based on chemical component of the soils on Nam Phong and Khon Buri catenae.

The factor analysis of the chemical properties of the soil on the Khon Buri catena (Figure 15) shows that about 67 percent of the variation in the data is explained by two factors. Four affinity groups of the chemical compositions are recognized on this catena. The first group encompasses Al_d, extractable Al, extractable acidity and Fe_d, the second group consists of Al_o, available P, available K, extractable K, Mn_p, OM, total N, Mn_d, Mn_o and Fe_o, the third group includes extractable Ca, pH KCl, pH H_2O, CEC, Fe_o/Fe_d, extractable Na, Extractable Mg, Fe_p and Al_p.

The soils on crest, backslope and footslope have moderate diversity in the chemical properties, which their surface soils (Ap-horizon) are quite different from the subsoils. However, the crest soil shows most uniform chemical properties in this catena. The soils on the higher positions do overlap in their chemical properties. The soil on the valley floor has a wide diversity in chemical properties which is distinctly different from the other soils on the landscape. The variation of chemical properties in Ap-horizon of the soil on the high positions and the soil on the valley are caused by the second and third group respectively.

5. The Relationship among the Chemical Properties of Soils on Catenae

The correlations matrix (Appendix I, Table 8) deals with the relationship among the soil chemical properties on catenae which the marked correlations are significant at $p<0.05$. The results show that three main groups of properties including organic matter, cation exchange capacity and clay content are related to other properties. Hence, their relationships will be discussed below.

5.1 Organic Matter Relates to Soil Properties

Organic matter shows a positive correlation with total N, available K, extractable K and Mn_p (Figure 16). These values tend to increase with the increase of organic matter content. The extractable K and available K show no relationship with the organic matter content in the soils on Nam Phong catena. This is possibly due to

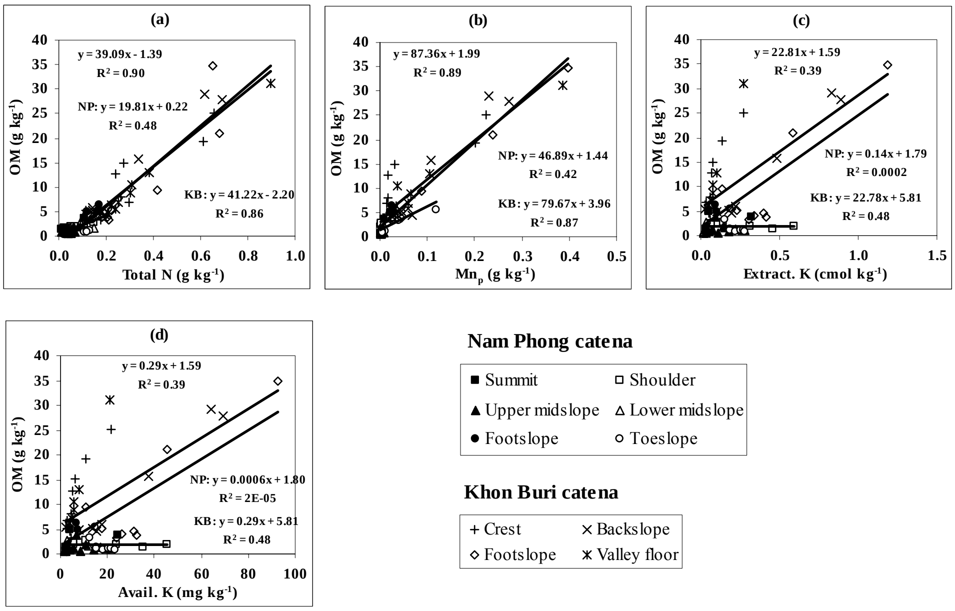


Figure 16 Scattering plot between the organic matter and total nitrogen (a), Mn_p (b), extractable K (c) and available K (d).

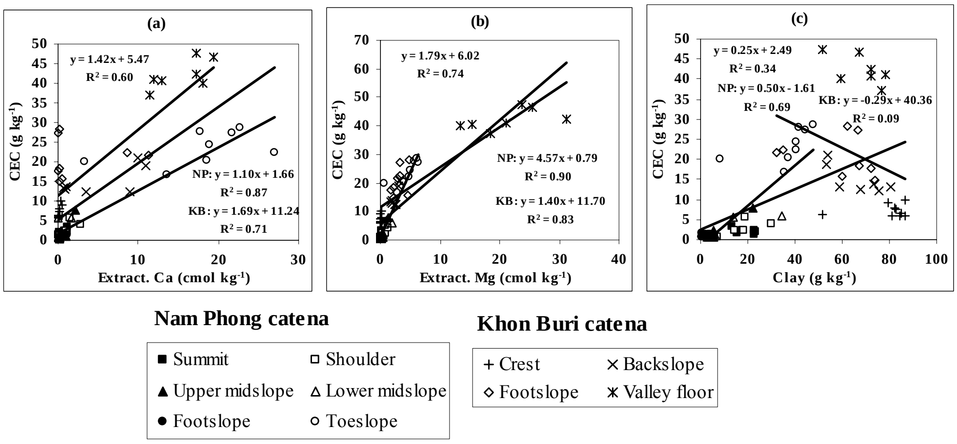


Figure 17 Scattering plot between cation exchange capacity and extractable Ca (a), extractable Mg (b) and clay content (c).

the potassium released from their parent rock. However, the organic matter can be the source of nitrogen, potassium and also the organic iron compound in the soils on both catenae as indicative by the high R^2 values (Figure 16).

5.2 CEC Relate to Soil Properties

The CEC and clay content are highly correlated on Nam Phong catena (R^2 = 0.69) as shown in Figure 17, which can generally be found in elsewhere (Sanchez, 1976; Young, 1976; Buol *et al.,* 1989, 1997; Osher and Buol, 1998), whereas there is no relationship between them for the soils on Khon Buri catena. However, the Ca and Mg are the main sources of the CEC in soils on both catenae (Fanning and Fanning, 1989; Anusorntpornperm, 1991; Brady and Weil, 1999, Panikron, 2002).

5.3 Clay Relates to Soil Properties

Figure 18 indicates that the free iron, aluminum and manganese are mainly in the clay fraction. This is associated to a presence of phyllosilicate minerals (kaolin, illite, smectite) and iron oxide minerals (goethite, hematite) as the major constituents in the clay fraction of upslope soils on both catenae especially those on the Khon Buri catena.

6. Synthesis

The chemical characteristics of the soils on both catenae are quite similar for the upslope soils and are significantly different from soils on the lowest position. Upslope soils have quite uniform chemical properties within the profiles whereas the toeslope and valley floor soils have wide variation in the chemical properties as shown by the results of factor analysis.

All soils at all positions on the catenae tend to have the highest organic matter content in the surface soil and a decrease with depth of organic matter in the profile. Total N, available P and available K follow the same trend of the organic matter content. This is common for soils in the Tropics (Sanchez, 1976; Young, 1976; Fanning and Fanning, 1989; Brady and Weil, 1999). The relationships between the organic matter content and N or K concentrations are highly positive indicating the release of the N and K to the soils from organic matter. Dominant chemical characteristics of upslope soils for both catenae are acidic condition related to the low basic cations concentration while soils at the lowest position on catenae are alkaline with the high extractable bases, especially Ca and Mg. Consequently, the CEC increases downslope which is attributed the leached cations that move to the lowest position on the landscape.

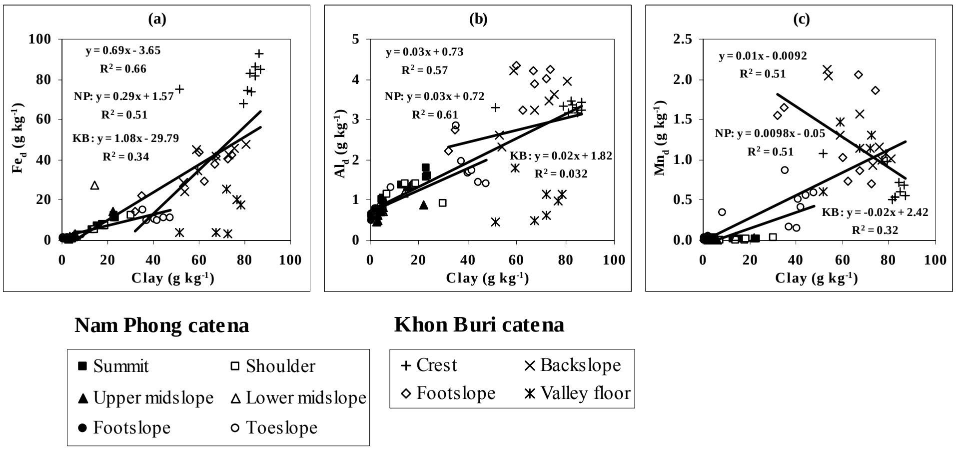


Figure 18 Scattering plot between clay content and Fe_d (a), Al_d (b) and Mn_d (c).

In general, the soils on the upper part of the catenae where well-drained conditions prevail contain more free iron and aluminium than do the poorly-drained soils at the base of a catena reflected in the gradual changes to of the red color to gray color of soils in the lowest position on the catena. Other reason for the low concentration of free iron and aluminum in the soils on the lowest position of landscape is the more poorly drained nature of these soils due to the periodic reduction and removal of dissolved iron in laterally seeping groundwater. The amorphous and organic forms of Fe and Al are positively correlated to the organic matter content in the soils.

All of these results lead us to a conclusion that leaching and translocation are the main pedogenic processes in the soils on the higher positions whereas cumulization is the major pedogenic process in soil on the lowest position of the catenae. The upslope soils having good physical properties but with quite poor plant nutrient status, are being used for field crops particularly for cassava growing. Other crops can possibly be grown on these soils but they need more specific management and more investment to gain satisfactory yields. The soils on the lowest positions on catenae are poorly drained with shallow groundwater are being used as paddy field. Their use sustainability can be increased immensely by adding some conservation practices into the system.

Mineralogy and Its Transformation in Soils on Nam Phong and Khon Buri Catenae

This part characterizes the dominant minerals in the sand, silt and clay fractions, and discuss the clay mineral formation and transformations in soils on Nam Phong and Khon Buri catenae. The semi-quantitative minerals in fine earth fractions for Nam Phong and Khon Buri catenae are given in Tables 4 and 5.

1. Mineral Component in the Clay Fraction

The minerals in the clay fraction of soils on Nam Phong catena are given in Table 4. The soil on the summit position contains much kaolin, and minor goethite and quartz, and traces of illite, vermiculite and hematite. The minerals in soil on the shoulder position are similar to that of the soil on the summit but hematite is absent. Soils on the midslope positions contain large amount of kaolin, moderate quartz and traces of illite and goethite. Quartz content decreases whereas illite increases with depth. Traces of vermiculite are present in the deeper horizons of soils on lower midslope position. Kaolin is a major constituent of soil on the footslope position and both quartz and illite are moderate constituents of this soil. A small amount of vermiculite is also present. For the toeslope soil on the lowest position on the Nam Phong catena, kaolin and illite are major constituents. Kaolin decreases and illite increases with depth. A small amount of vermiculite is also present and it increases with depth. Soils on upper positions on the catena experience a leaching, base depleting environment due to the high rainfall resulting in the formation of kaolin (Vijarnsorn and Fehrenbacher, 1973; Gallez *et al.*, 1976; Boonsompoppunth, 1981; Suddhiprakarn *et al.*, 1985). A relatively more abundance of illite in the soils on the footslope and toeslope positions reflect to a lower intensity of weathering and illite derived from the sedimentary parent rock. In the toeslope soil where leached material from upslope accumulate a higher pH and geochemical environment favor retention of illte (Fanning *et al.*, 1989). Additionally the toeslope soil has formed upon a fine grained illitic sediment that can contribute much illite to the profile (Olsen *et al.,* 2000; Thompson and Ukrainczyk, 2002).

Table 4 Semi-quantitative mineralogical analysis of soils on Nam Phong catena

Depth	Horizon	Clay						Silt	Fine sand
		Kao	Ill	Ver	He	Goe	Q	Q	Q
Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic									
0-20	Ap	xxx	nd	tr	tr	x	x	xxxx	xxxx
20-40	E	xxx	tr	tr	tr	x	x	xxxx	xxxx
59-73	Bt2	xxx	tr	tr	tr	x	x	xxxx	xxxx
142-172	Bt5	xxx	tr	tr	tr	x	x	xxxx	xxxx
Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic									
0-23	Ap	xxxx	nd	nd	nd	x	x	xxxx	xxxx
23-35	E	xxx	tr	nd	nd	x	x	xxxx	xxxx
58-82	Bt2	xxx	tr	nd	nd	x	x	xxxx	xxxx
Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic									
0-20/30	Ap	xxx	tr	nd	nd	tr	xx	xxxx	xxxx
30-45	E	xxx	tr	nd	nd	tr	xx	xxxx	xxxx
67-100	Bt2	xxx	x	nd	nd	tr	x	xxxx	xxxx
155-182	Bt5	xxx	x	nd	nd	tr	x	xxxx	xxxx
Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic									
0-27/35	Ap	xxx	x	nd	nd	tr	xx	xxxx	xxxx
46-63	Bt2	xxx	x	x	nd	tr	x	xxxx	xxxx
80-100	2BC	xxx	x	x	nd	tr	x	xxxx	xxxx
Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic									
0-10/20	Ap1	xxx	x	tr	nd	tr	xx	xxxx	xxxx
30-45	Bw	xxx	xx	tr	nd	tr	xx	xxxx	xxxx
45-80	Bt	xxx	xx	tr	nd	tr	xx	xxxx	xxxx
110-130+	Btg2	xxx	xx	tr	nd	tr	xx	xxxx	xxxx
Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic									
0-5	Apg	xx	xx	x	nd	tr	nd	xxxx	xxxx
5-23/30	Btcg	xx	xxx	x	nd	tr	nd	xxxx	xxxx
30-48	Btg1	xx	xxx	x	nd	tr	nd	xxxx	xxxx
80-113	Btg3	x	xxx	xx	nd	nd	nd	xxxx	xxxx
162-195+	BCg2	x	xxx	xx	nd	nd	nd	xxxx	xxxx

Kao = kaolinite; Ill = illite; Ver = vermiculite; He = hematite; Goe = goethite and Q = quartz
tr = < 5%; x = 5-20%; xx = 20-40%; xxx = 40-60%; xxxx = > 60% and nd = not detected.

For Khon Buri catena, kaolin dominates the clay in the three upslope profiles with abundant smectite in the valley floor soil (Table 5). A small amount of anatase is present in all soils. Traces of interstratified 1.0-1.4 nm mineral occur in soils on the backslope and footslope positions. Depth function of clay minerals reveals uniform distribution of kaolin with depth in the crest profile, increasing with depth in backslope profile and decreasing with depth in valley floor profile. In contrast, semectite dominates clay fraction in the valley floor profiles with an increasing trend with depth.

Table 5 Semi-quantitative mineralogical analysis of soils on the Khon Buri catena

Depth	Horizon	Clay						Silt								Fine sand					
		Kao	Int	Sm	He	Goe	Ana	Q	He	Goe	Kao	Ana	Ru	Fel	14 gr.	Q	He	Goe	Kao	Fel	Ana
Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic																					
0-15	Ap1	xxxx	nd	nd	xxx	nd	x	xxxx	x	nd	x	x	nd	nd	nd	xxxx	x	nd	tr	nd	nd
30-51	Bto1	xxxx	nd	nd	xx	nd	x	xxxx	x	nd	x	x	nd	nd	nd	xxxx	x	nd	tr	nd	nd
73-100	Bto3	xxxx	nd	nd	xx	nd	x	xxxx	x	nd	x	x	nd	nd	nd	xxxx	x	nd	x	nd	nd
130-160	Bo1	xxxx	nd	nd	xx	nd	x	xxxx	x	nd	x	x	x	nd	nd	xxxx	x	nd	x	nd	nd
185-205+	Bto5	xxxx	nd	nd	xx	nd	x	xxxx	x	nd	x	x	nd	nd	nd	xxxx	x	nd	x	nd	nd
Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic																					
0-11	Ap1	xxxx	nd	nd	nd	xx	x	xxxx	x	tr	x	x	nd	nd	nd	xxxx	tr	tr	tr	nd	tr
30-59	Bt1	xxxx	nd	nd	nd	xxx	x	xxxx	tr	x	x	x	nd	nd	nd	xxxx	tr	x	x	nd	tr
88-119	Bt3	xxxx	tr	nd	nd	xx	x	xxxx	tr	x	x	tr	tr	nd	nd	xxxx	tr	x	x	nd	tr
119-151+	BCr1	xxxx	tr	nd	nd	xxx	x	xxxx	x	x	x	x	tr	nd	nd	xxxx	tr	x	x	nd	tr
Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic																					
12-30	Ap2	xxxx	nd	nd	x	xx	x	xxxx	tr	nd	tr	x	tr	nd	tr	xxxx	tr	tr	tr	nd	tr
30-52	Btc1	xxxx	tr	nd	tr	xx	x	xxxx	tr	nd	tr	x	tr	nd	nd	xxxx	tr	tr	tr	nd	tr
72-103	Btc3	xxxx	nd	nd	x	xx	x	xxxx	tr	tr	tr	x	tr	nd	nd	xxxx	tr	tr	x	nd	tr
130-150	Btc5	xxxx	tr	nd	tr	xx	x	xxxx	nd	tr	tr	x	tr	nd	nd	xxxx	tr	tr	x	nd	tr
150-180+	BCrt	xxxx	x	nd	tr	xx	x	xxxx	nd	tr	tr	x	x	nd	nd	xxxx	tr	tr	x	nd	tr
Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic																					
0-15	Apg	xx	nd	xxx	nd	x	x	xxxx	nd	tr	tr	x	tr	tr	nd	xxxx	nd	tr	tr	tr	tr
25-50	Bssg	xx	nd	xxxx	nd	x	x	xxxx	nd	tr	tr	x	nd	tr	tr	xxxx	nd	nd	tr	tr	tr
76-100/110	Bg2	x	nd	xxxx	nd	nd	x	xxxx	nd	tr	tr	x	nd	tr	tr	xxxx	nd	nd	tr	x	nd
133-160	BCg2	x	nd	xxxx	nd	nd	x	xxxx	nd	nd	tr	x	nd	tr	tr	xxxx	nd	nd	tr	x	nd
160-180+	Crg	x	nd	xxxx	nd	nd	x	xxxx	nd	nd	tr	x	nd	tr	x	xxxx	nd	nd	tr	tr	nd

Kao = kaolin; Int = Interstratified 10 Å and 14 Å minerals; Sm = smectite, 14 gr. = 14 Å mineral group; He = hematite, Goe = goethite; Q = quartz, Ana = anatase, Ru = rutile, and Fel = feldspar
tr = < 5%; x = 5-20%; xx = 20-40%; xxx =40-60%; xxxx = > 60% and nd = not detected

The crest soil contains only hematite while both goethite and hematite are present in soils on the backslope and footslope positions. Goethite occurs only in the near surface horizons of the valley floor soil and hematite is absent in most profiles. Soil on the valley floor is poorly drained and saturated with water for at least some of the year. Reduced iron together with dissolved ions (Si, Al, Mg) leached from the profiles upslope may have reacted to form smectite (Harder, 1972).

2. Mineral Component in the Silt and Fine Sand Fractions

All soils on Nam Phong catena contain only quartz in both silt and fine sand fractions (Table 4) due to the parent materials of this catena being colluvium derived from sandstone for the soil on the summit, shoulder, midslope and footslope positions. The sandstone contains low amount of that sand sized primary minerals. The soil on toeslope position has developed at least in part from residuum of a fine grained sedimentary rock. In addition, quartz is highly resistant mineral in soils (Sudom and Arnaud, 1971; Cornu *et al.*, 1999; Stiles *et al.*, 2003).

The mineralogical distribution patterns of silt and fine sand fractions are quite similar along the Khon Buri catena (Table 5). The mineralogy of silt and fine sand fractions is dominated by quartz which can be ascribed to the selective accumulation due to its relative resistance to weathering (Murali *et al.*, 1978). Quartz is not commonly a significant constituent of basalt (Mackenzie and Adams, 1994) so the large amounts of quartz in the silt and sand fractions can be authigenic particularly on the lower part of the catena (McKeague and Cline, 1963; Singer, 1967; Eswaran, 1971). Kaolin, iron oxides and anatase are present in both silt and fine sand fractions in all profiles (Harris *et al.*, 1985). Traces of feldspar and the 1.4 nm mineral occur in silt and sand fractions of the valley floor soil. The persistence of these minerals may be consequence of the less intense weathering under alkaline condition at this position (Birkland, 1999; Buol *et al.*, 2003).

Table 6 Coherently scattered domain (CSD) and width at half height (WHH)of the dominant minerals in clay fraction of soils on Nam Phong and Khon Buri catena[1/]

Depth	Horizon	Kaolin (nm)				Illite (nm)				Vermiculite (nm)			
		CSD001	WHH	CSD002	WHH	CSD001	WHH	CSD002	WHH	CSD001	WHH	CSD100	WHH
						Nam Phong catena							
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic												
0-20	Ap	12.8	0.626	12.4	0.656								
20-40	E	11.6	0.688	14.2	0.573								
59-73	Bt2	12.3	0.650	13.0	0.625								
142-172	Bt5	11.4	0.701	13.6	0.597								
	Shoulder: Psammentic Kandiustalf, sandy, siliceous, isohyperthermic												
0-23	Ap	11.0	0.724	11.5	0.710								
23-35	E	11.6	0.687	12.8	0.635								
58-82	Bt2	11.3	0.704	12.8	0.635								
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic												
0-20/30	Ap	10.5	0.762	14.3	0.569	36.5	0.218	13.6	0.590				
30-45	E	10.8	0.740	14.6	0.557	35.5	0.114	14.1	0.572				
67-100	Bt2	11.0	0.727	13.9	0.585	44.0	0.181	8.1	0.992				
155-182	Bt5	13.0	0.617	11.9	0.681	7.3	1.095	18.4	0.437				
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic												
0-27/35	Ap	10.8	0.738	11.7	0.698			20.4	0.395				
46-63	Bt2	11.5	0.694	13.9	0.584	1.4	5.890	9.1	0.885				
80-100	2BC	10.5	0.758	13.0	0.628	16.8	0.473	7.7	1.043				
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic												
0-10/20	Ap1	10.8	0.739	12.9	0.631	8.4	0.952	39.0	0.206				
30-45	Bw	10.7	0.745	11.3	0.720	1.3	6.075	8.4	0.953	9.4	0.845	22.5	0.360
45-80	Bt	9.9	0.809	12.5	0.650	5.0	1.587	6.1	1.323	14.4	0.554	16.5	0.490
110-130+	Btg2	10.3	0.774	11.4	0.713	1.3	5.924	23.6	0.340	15.5	0.514	17.6	0.460
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic												
0-5	Apg	6.0	1.324			1.3	6.067	6.7	1.200	12.8	0.620	14.8	0.545
5-23/30	Btcg	10.1	0.791			1.3	6.205	7.6	1.063	11.8	0.677	20.1	0.403
30-48	Btg1	0.8	9.633			1.3	6.223	7.6	1.065	37.5	0.212	22.9	0.353
80-113	Btg3	6.4	1.253			1.3	6.283	7.3	1.101	2.4	3.256	19.0	0.425
162-195+	BCg2	7.8	1.025			1.3	6.213	6.9	1.165	18.8	0.424	24.0	0.337

Table 6 (Continued)

Depth	Horizon	Kaolin (nm)				Smectite (nm)				Goethite (nm)		Hematite(nm)			
		CSD001	WHH	CSD002	WHH	CSD001	WHH	CSD 002	WHH	CSD110	WHH	CSD104	WHH	CSD 110	WHH
		Khon Buri catena													
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic														
0-15	Ap1	17.5	0.456	19.50	0.418							18.8	0.440	28.2	0.296
30-51	Bto1	17.0	0.469	20.00	0.407							19.7	0.420	26.5	0.315
73-100	Bto3	18.5	0.432	15.70	0.517							15.9	0.520	27.4	0.305
130-160	Bo1	16.7	0.478	20.60	0.395							20.4	0.407	29.5	0.283
185-205+	Bto5	16.9	0.473	19.10	0.426							17.1	0.486	23.0	0.363
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic														
0-11	Ap1	14.2	0.563	17.40	0.467					11.8	0.686				
30-59	Bt1	15.2	0.525	15.80	0.516					9.4	0.857				
88-119	Bt3	15.4	0.520	17.00	0.478					14.6	0.553				
119-151+	BCr1	15.5	0.514	18.30	0.445					12.8	0.632				
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic														
0-15	Ap2	11.3	0.709	11.80	0.688					9.5	0.848	10.2	0.815	20.4	0.410
30-52	Btc1	10.6	0.755	12.00	0.676					13.1	0.616	19.7	0.420	16.4	0.510
72-103	Btc3	11.8	0.679	12.10	0.674					8.8	0.920	13.8	0.600	12.7	0.657
130-150	Btc5	10.7	0.750	14.60	0.557					8.8	0.920	13.0	0.637	13.3	0.630
150-180+	BCrt	12.3	0.648	14.00	0.580	2.4	3.357			9.2	0.880	17.8	0.465	14.4	0.579
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic														
0-15	Apg	13.9	0.574	15.60	0.521	2.4	3.279								
25-50	Bssg	13.8	0.579	17.50	0.466	2.4	3.364								
76-100/110	Bg2	13.3	0.599	14.70	0.554	2.4	3.326								
133-160	BCg2	13.8	0.578	16.20	0.501	5.1	1.556	12.8	0.629						
160-180+	Crg	13.8	0.578	16.30	0.499	5.9	1.354	16.4	0.489						

[1/] performed on the XRD patterns of the oriented clay on porous plate using the X-pas software (Singh and Gilkes, 1992a).

3. Characterization of Dominant Minerals in Clay Fraction for Both Catenae

3.1 Kaolin

Kaolin is dominant mineral in the clay fraction for both two soil catenae especially in the high positions on the landscape. The kaolin content decreases and the 2:1 type clay minerals increase downslope for both catenae. The dominance of kaolin is consistent with the highly weathered condition and high development stage of most of these soils, and similar observations have been made for highly weathered soil condition from other part of the world (Juo, 1980). The characteristic of the kaolins may strongly influence the physical and chemical properties of soils. There reflect that the soils on the high positions of the landscape are inherently very low in fertility.

In soils on Nam Phong catena, the coherently scattered domain (CSD) of kaolin slightly decreases down the landscape (Table 6). The CSD of kaolin in the upslope soils is quite uniform, ranging between 10-11 nm while the CSD of kaolin in the toeslope soil varies between 0.8-10 nm. Soil kaolin has a small range of the width at half height (WHH) values and the toeslope soil shows the highest WHH of the kaolin crystal. For Khon Buri catena, the CSD ranges between 11-17 nm and the crest soil shows the highest CSD of the kaolin crystal. The WHH of the 001 kaolin plane ranges from 0.4-0.75. The CSD decreases downslope similar to that on Nam Phong catena. Generally, a crystal size of kaolin of soils formed on basalt is smaller than those derived from sandstone (Hart *et al.*, 2002a, 2003; Varajao *et al.*, 2001). However, the kaoline crystals of the soils on Khon Buri catena are larger than those of the Nam Phong catena probably because of iron or organic matter acting like cementing agent to bind the crystals together. This makes the crystals bigger than usually are (Brindley and Brown, 1980).

Representative TEM images of the clay fraction for Nam Phong and Khon Buri catenae are given in Figures 19 and 20. They clearly demonstrate the wide range of sizes and shapes of the kaolin crystals. Mostly form of kaolins are hexagonal plates with a few subhedral and rounded plates for both catenae. The variability in the

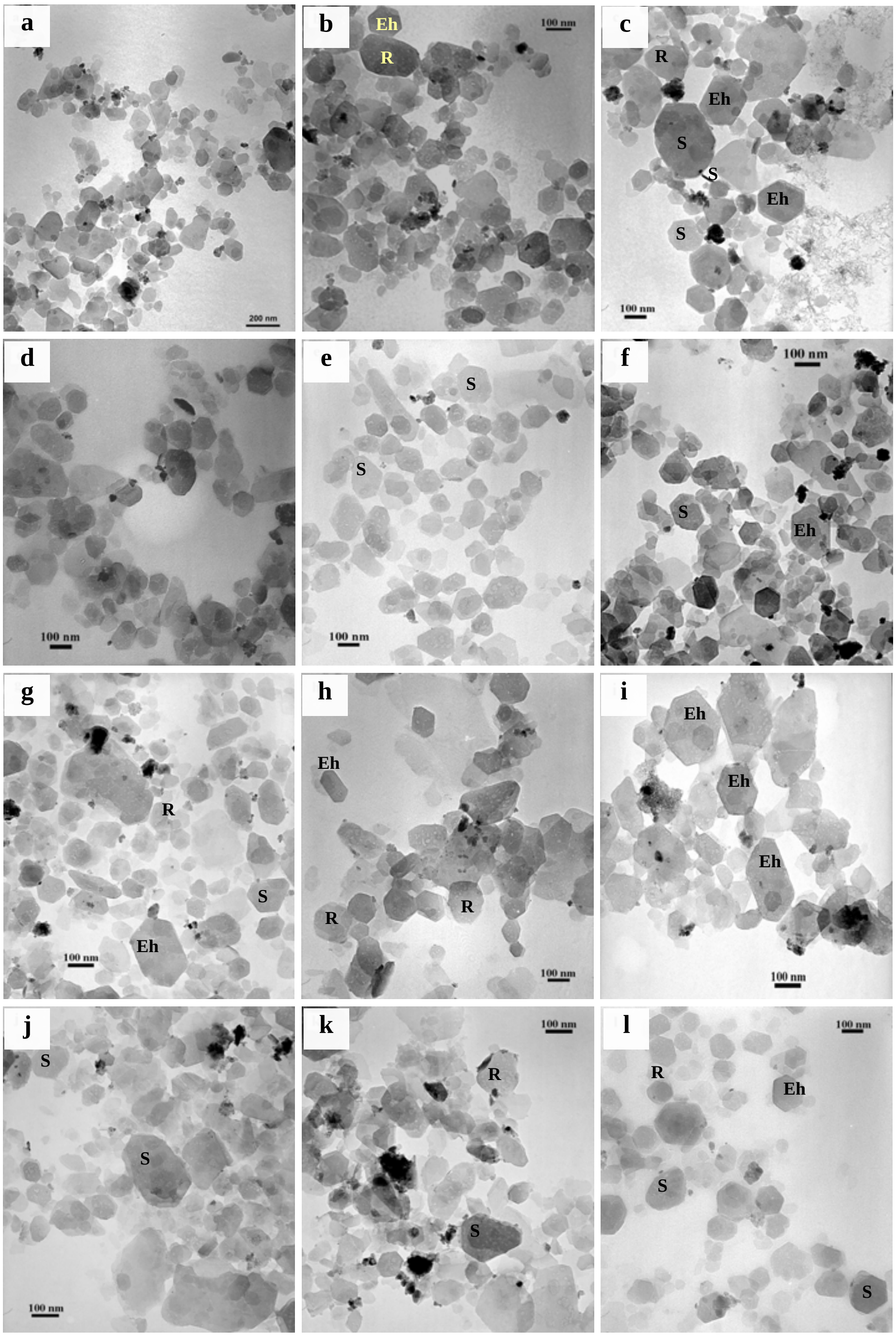


Figure 19 TEM micrographs of the clay suspension of the upslope soils at summit (a, b, c), shoulder (d, e, f), upper midslope (g, h, i) and lower midslope (j, k, l) on Nam Phong catena showing dominance of kaolin with marked variation in crystal morphology and size. Various morphological types of kaolin crystals are indicated: E = elongated, Eh = euhedral hexagonal, R = rounded and S = subhedral.

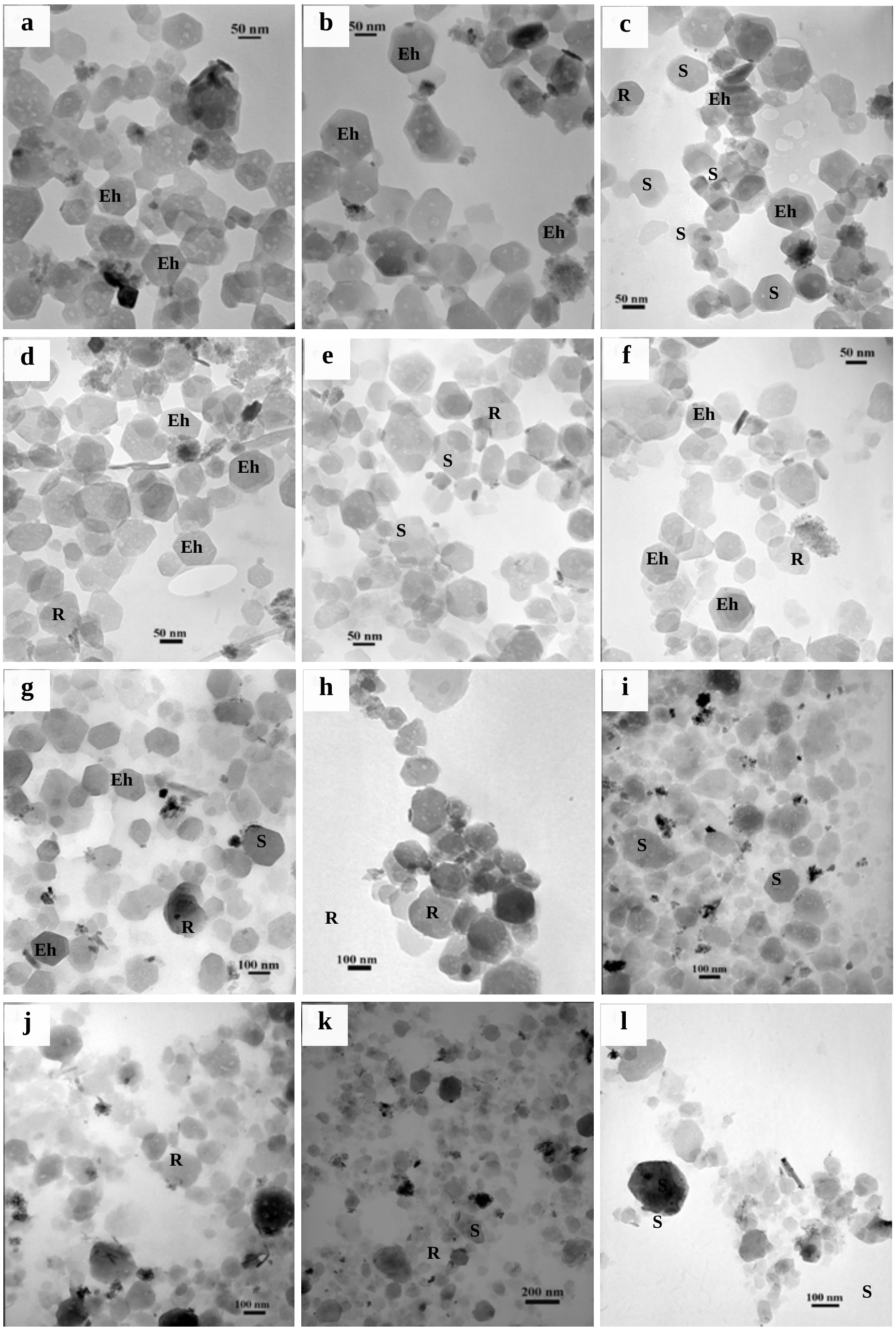


Figure 20 TEM micrographs of the clay suspension of the upslope soils at crest (a, b, c, d), backslope (e, f, g, h) and footslope (i, j, k) on Khon Buri catena showing dominance of kaolin with marked variation in crystal morphology and size. Various morphological types of kaolin crystals are indicated: E = elongated, Eh = euhedral hexagonal, R = rounded and S = subhedral.

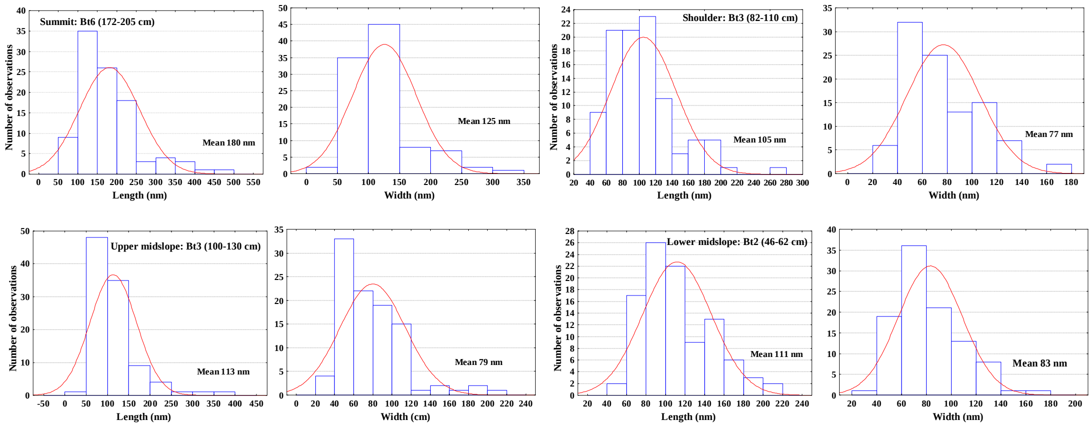


Figure 21 Histograms of the longest and shortest width of the individual kaolin crystal for Nam Phong catena. Note that 100 individual kaolins measured from TEM image.

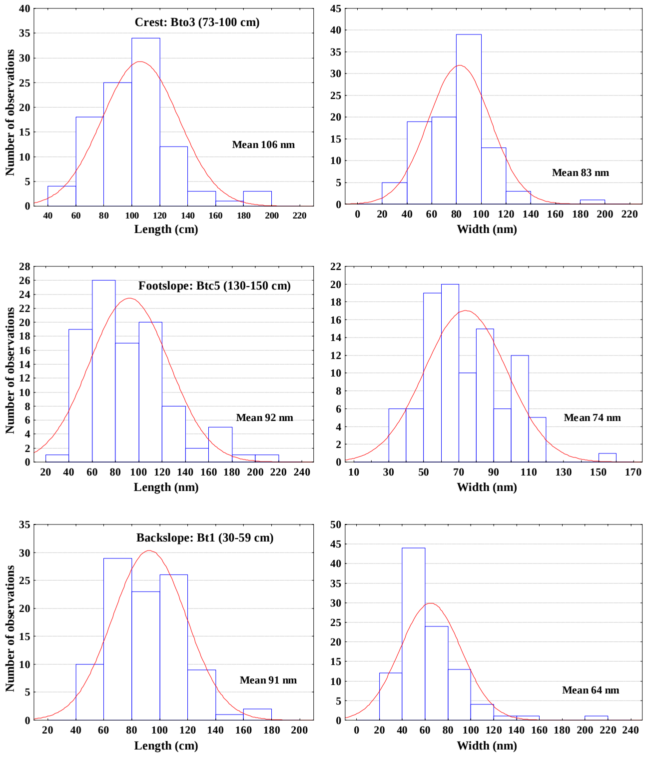
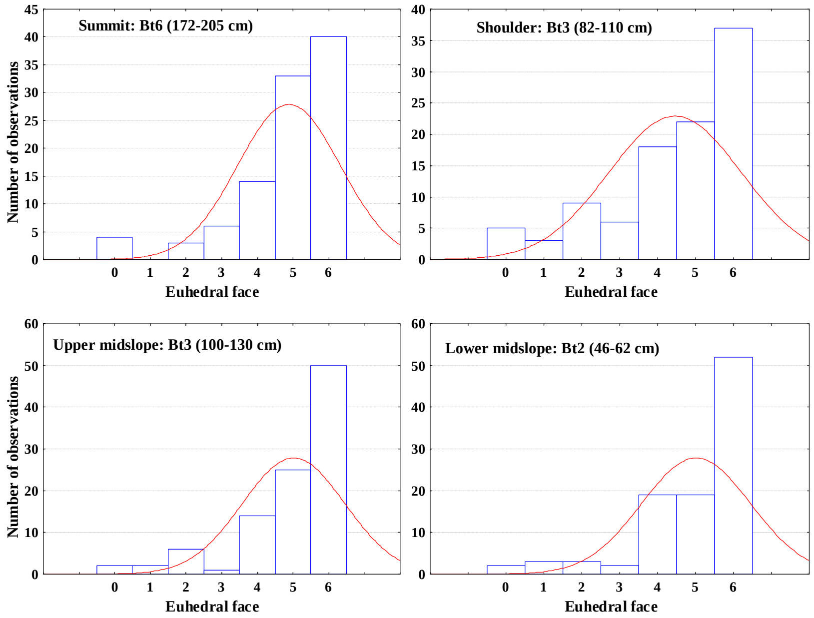


Figure 22 Histograms of the longest and shortest width of the individual kaolin crystal for Khon Buri catena. Note that 100 individual kaolins measured from TEM image.

kaolin morphology is common and widespread in natural deposits. This might be due to the variability in iron content of the kaolin (Singh and Gilkes, 1995, Hart *et al.*, 2002a, 2003; Varajao *et al.*, 2001).

(a) Nam Phong catena



(b) Khon Buri catena

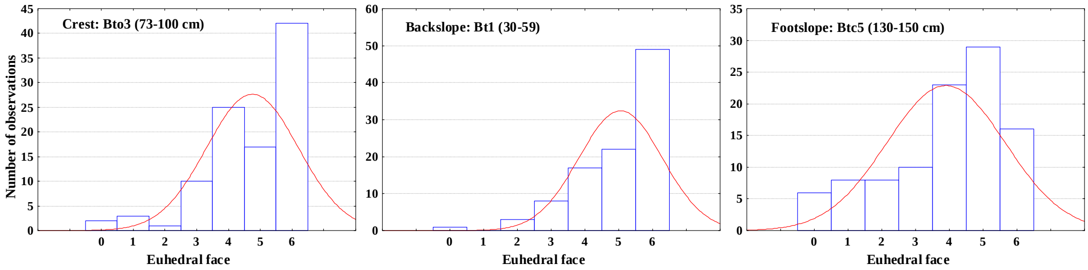


Figure 23 Distributions of euhedral face of the individual kaolin crystals for the Nam Phong (a) and Khon Buri (b) catenae based on the TEM image.

The size and shape of 100 kaolin crystals in soils were measured for each positions on the landscape to provide quantitative values of these variations. The longest and shortest width and percentage of euhedral faces on each crystals were measured. The histograms (Figures 21, 22 and 23) show that the length and width of kaolin crystals are smaller on lower parts of the landscape for both catenae. This ispossibly due to higher moisture content downslope. However, the kaolin crystals of soils on Nam Phong catena are larger than those of soils on Khon Buri catena. Normally kaolin crystals of soils developed on sedimentary rock is larger than those of soils developed on the igneous rock (Dixon, 1989; Singh and Gilkes, 1992b, Hart *et al.*, 2003). The kaolin crystals mostly have complete euhedral faces suggesting a quite low fertility status of the upslope soils on both catenae (Dixon, 1989; Johnson and Comerford, 1999; Schulze *et al.*, 1999).

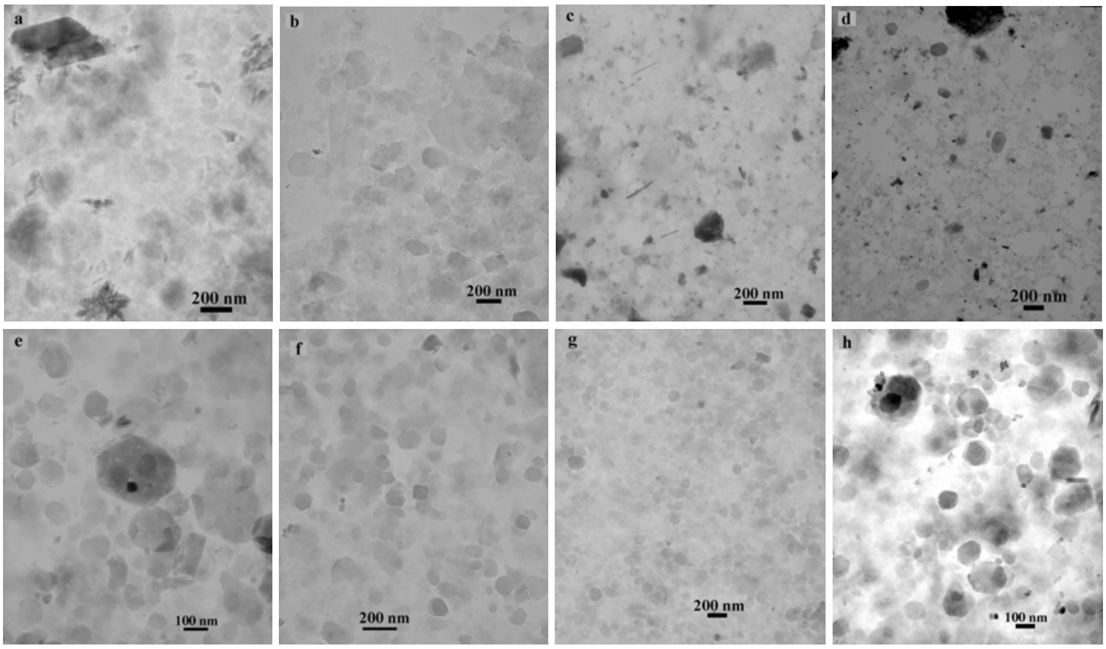


Figure 24 Transmission electron micrographs (TEM) of the clay fraction of the toeslope soil on Nam Phong (a, b, c, d) and valley floor soil on Khon Buri catena (e, f, g, h) showing the mixture of kaolin and 2:1 minerals.

3.2 Illite

Illite is dominant in the clay fraction of the soils on the low position on Nam Phong catena especially toeslope position. The TEM images (Figures 24a-24d) of the clay fraction of the toeslope soil show illite content quite equal to or more than kaolin content (data from the XRD). The mixture of the kaolin crystals with clouded crystals might be illite (Grim, 1968). The CSD of the illite in the toeslope soil is very small resulting in the cloudy mixture. However, illite crystals of this catena have a wide range of the CSD (1.3-44 nm) and decrease downslope (Table 5). In addition, WHH values (6.0-6.2) exhibit broad reflection confirming a small illite crystal (Brinley, 1980; Reynold, 1980; Thompson and Ukrainczyk, 2002).

3.3 Smectite

Smectite is a dominant mineral of soil in valley floor on Khon Buri catena. The XRD patterns of the top horizons (Figure 25) show broader and more diffuse

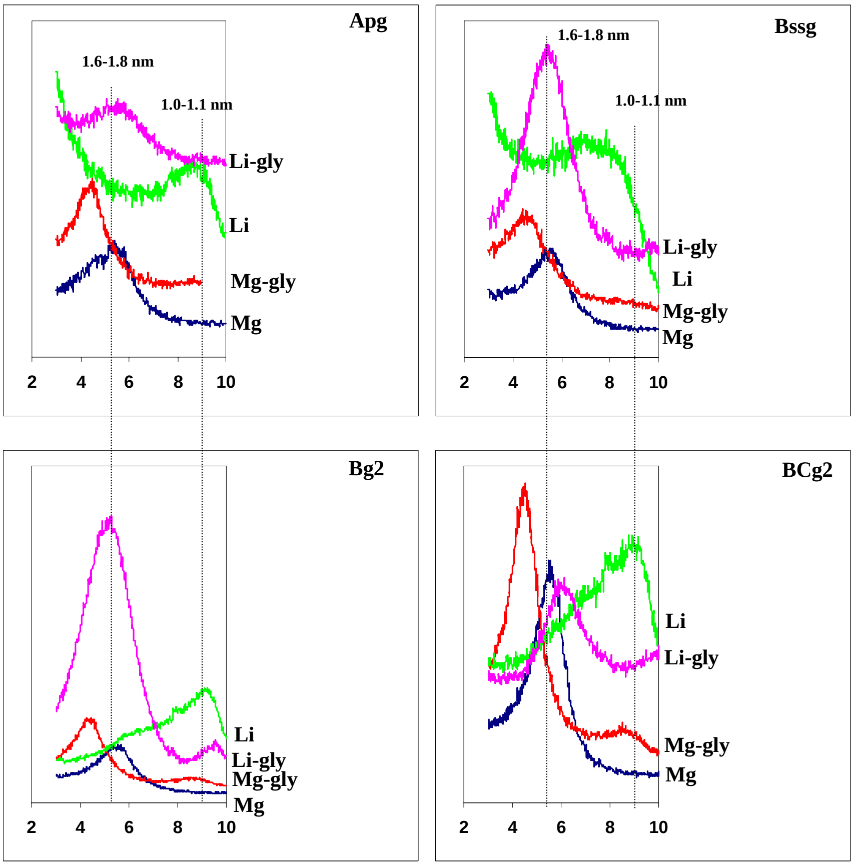


Figure 25 XRD pattern for identification of smectite species of some horizons of the valley floor soil on Khon Buri catena, showing a presence of beidellite based on the clay saturated with $LiCl_2$. Note that oriented clay were treated by saturation with $MgCl_2$ (Mg) and subsequent glycerol salvation (Mg-gly) at room temperature (25^oC); saturated with $LiCl_2$ and heated at 300^oC (Li) and subsequent glycerol salvation (Li-gly).

peak than those of the deeper horizons possibly due to the high Na concentration (Harder, 1972). Further suggestion is the neoformation of smectite might have contributed to the diffuse diffraction (Reid *et al.*, 1996). According to Schulze (1989) the broaden peaks are a function of decreasing particle size. In this study the smectite particle increases slightly with depth (Figure 25). Neoformed smectites may be poorly crystalline, further contributing to peak broadening (Reynold, 1980). Smectite precipitated from solution is expected to be of smaller particle size than either transformed or inherited smectite. All of these lead to an interpretation that the smectite in upper horizon of soils on the valley floor position comes from neoformation or precipitation from solution might be Mg enriched while those in the lower position probably be inherited smectite. The level of Mg is possibly the most important factor for synthetic smectite formation from the basic rock (Harder, 1972). Weaver *et al.* (1971) and Reid *et al.* (1996) noted that the high concentration of Si and basic cation especially Mg are essential chemical condition for the neoformation of montmorillonite. The TEM images of the clay fraction of the valley floor soil (Figures 24e-24h) show small smectite mean crystals size (CSD: 2.4-5.9 nm) reflecting the cloudy mixture with the kaolin crystals.

The Greene and Kelley method is allowed to identify the smectite species. The Li-saturated clay is heated to 300 ^{o}C and then glycerol treated, after heating all smectites collapse approximately to 0.1 nm., and after subsequent glycerol salvation beidellite expands to about 1.8 nm whereas the collapse of montmorillonite is irreversible (Greene-Kelley, 1953; Lim and Jackson, 1986; Singh and Gilkes, 1991) which are shown in Figure 25 indicating a presence of beildellite in this soil profile. Beildellite is commonly found in the lowland soils derived from basalt (Pal and Deshpande, 1987).

3.4 Iron oxides

The crystalline forms as goethite and hematite are iron oxide species which commonly found in the upslope soils on both catenae, however their contents are quite low in the soils on Nam Phong catena. Only trace goethite is present in surface soils of the toeslope and valley floors. This attributes the environmental conditions and parent material influencing weathering rate of iron bearing minerals and the proportions of the secondary oxide forms. The influences of iron oxide in soils are mainly in the exhibition of red color and good soil aggregation. This is contributed by a very small particle of iron oxide coated on the clay particle inducing the red color prevailing in the soil matrix and also resulting in the aggregation of the clay.

The CSD of 104 and 110 dimensions of the hematite in upslope soils on khon Buri catena ranges from 10-20 and 13-20 nm respectively, and increase with depth. The CSD of hematite of the footslope soils is smaller than those of the crest soils. In the case of goethite, their CSD along the 110 direction of the backslope soil is equal to those of the footslope soil (Table 6). The WHH of the hematite and goethite are uniform among the slope positions on catena. As the results, hematite and goethite in these soils are quite small and might be influenced by several pedogenic factors such as organic matter content, pH and pedoenvironmental condition (Schertmann, 1988).

4. Clay Mineral Transformation on Catenae

4.1 Illite-Vermiculite-Kaolin on Nam Phong catena

The relative abundance of kaolin decreases as the relative abundance of illite increases, down the slope on Nam Phong catena. This relationship can easily be attributed to the degree of weathering of the soils. In general as the intensity of weathering increases the relative abundance of illite decreases. The relationship of SiO_2-Al_2O_3-$MgO+K_2O+CaO$ of the clay fraction (Figure 26) indicates that toeslope soil has a relatively higher amount of the basic cations. The basic cations are leached from the upper slope position and released from the primary mineral that might be mainly feldspar, accumulate in the lowest position on the landscape where the poorly drained condition prevails. This is attributed to alkaline condition that occurs, especially high in K concentration which is suited for the illite formation. Feldspar has been altered to illite in the poorly drained soils and subsequently illite transformed to kaolin during the intense weathering under the well drained condition. In addition, the broadening of basal reflections (WHH=6.0-6.2) of illite might be explained in terms of kaolinization of illite (Duzgoren-Aydin *et al.,* 2002).

In addition, an increase of illite coupled with the decrease of vermiculite within the toeslope profile support a possibility of illite transformed from vermiculite (i.e., K-fixation and collapse of swelling layers; Sroden and Eberl (1984)). Sroden and Eberl (1984) proposed that the cycles of wetting and drying, due to a water table fluctuating generated mottles through redox reactions of iron and that was coupled with transformation of detrital vermiculite to ordered illite-smectite.

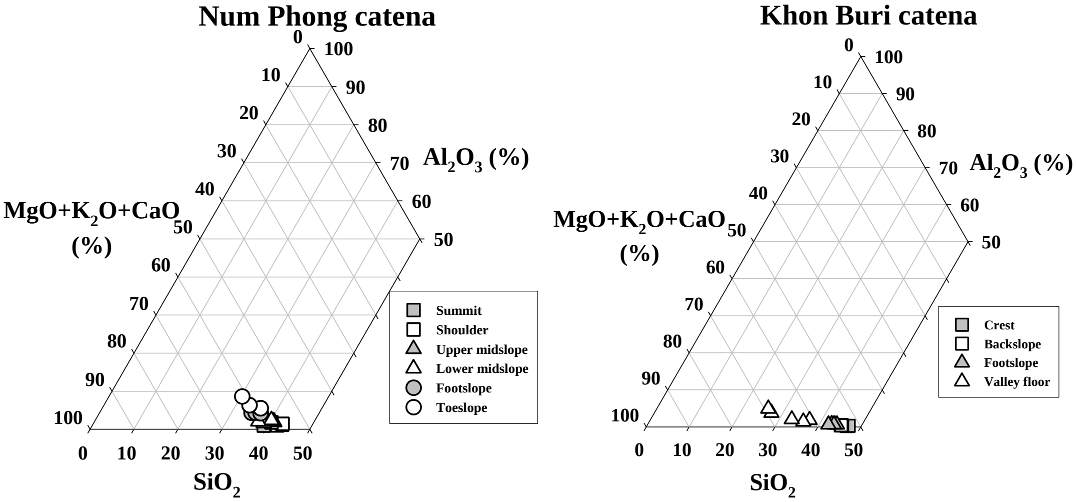


Figure 26 Ternary graphs of SiO_2-Al_2O_3-MgO+K_2O+CaO in the clay fraction for Nam Phong and Khon Buri catenae.

4.2 Smectite-Kaolin on the Khon Buri catena

The formation of minerals in the basaltic catenary soils was proposed that the physical and chemical processes weather the basalt rock. Resulting in it was broken parts that permitted a penetration of air and water maintained in primary minerals in basalt, favoring the transformation to smectite, kaolin and ferric oxide. The difference in intensity of weathering results in various minerals. In early stage of weathering basalt under poorly drained environment as represented in the valley floor profile, produce a base rich environment under limited leaching condition especially in lower horizon, thus induce inherited smectite formation. The high Mg content of the upper horizon favors a precipitation of smectite from solution. However, a small amount of kaolin can be present in this situation (Grim, 1968; Dixon, 1989). The iron coming from weathered primary minerals might be contained in smectite structure (Stucki, 1988) or found in form of amorphous (Schwertmann, 1988). Therefore in this study iron oxide minerals cannot be detected by XRD in the valley floor profile. A mature stage of weathering under well drained condition as represented in backslope profile induces an oxidizing condition, providing more kaolin and iron oxide formed from primary minerals or smectite. The conversion of smectite to kaolin is attended by the loss of bases especially Mg (Harder, 1972) under acid environment. Prudeneio *et al.* (2003) proposed that unstable smectite is due to an increase in Mg activity in interstitial waters, associated with a high hydrostatic pressure, leading to distortion of phyllosilicate structure. Iron oxides are hydrated and dehydrated during alternating wet and dry seasons such prevail in this position and then they become stable and crystallized. Furthermore, a presence of smectite in BCrt-horizon might be inherited while an origin of smectite in the top soil horizon is not clear. In the highly stage of weathering under well drainede condition as represented in the crest profiles, their situation is quite the same to those of backslope profile although there is no activity of water table. There are only kaolin and iron oxides in this position probably being due to a more advanced weathering. Therefore all smectite transformed to kaolin and most of iron forms are found as hematite form due to the driest condition of this position.

5. Synthesis

Kaolin is the major clay mineral in the upslope soils on both catenae. The 2:1 clay mineral is dominant mineral in the clay fraction of the soils on the lowest positions on the landscape which their type depending on the type of basic cation. The relatively high K and Mg in the soil solution induce the formation of illite and smectite respectively. Quartz is mainly a constituent in the silt and sand fractions for both catenae however traces of hematite, goethite and anatase exist in the silt and sand fractions of the Khon Buri catena. From these systematic mineralogical results, it is postulated that all soils on Nam Pong catena developed on the sedimentaries possibly be sandstone and shale and all soils on Khon Buri catena formed on basalt. However, all soils on both catenae are highly weathered soils.

Kaolin crystals are mostly euhedral hexagonal plate with CSD ranging from 0.8-18 nm and the kaolin of soil on Khon Buri catena are larger than those of Nam Phong catena probably due to kaoline crystals were cemented by iron or organic. In contrast, the length (105-180 nm) and width (77-125 nm) of kaolin of soils on Nam Phong are greater than those of the Khon Buri catena (91-106 nm length, 64-83 nm width). However, the kaolin crystal size decreases down the slope. This reflects quite low fertility status of the upslope soils on both catenae. Illite is mainly clay mineral in the toeslope soil on Nam Phong, beidellite which identified by Green and Kelly method, is dominant mineral in the valley floor soils on Khon Buri catena. In this case, the toeslope and valley floor soils have more fertility status. For the iron oxide minerals, hematite and goethite are commonly found in upslope soils on both catenae. However the relativly higher content of iron oxides in the soils on Khon Buri catena is attributed to a high iron bearing parent rock. Very small iron oxide particles coating on clay particle exhibit red and yellow colors and influence the forming of soil structure.

Hence, the type of clay minerals on both catenae reflects environmental conditions including moisture, concentration of cations in solution and the degree of weathering. At the lower position, the high base status derived from parent rock and the accumulation of leached ions from the upslope soils under poorly drained condition, induce illite and smection formation. In contrast, the intense weathering condition of soils at the higher positions on the catenae with base depleting environment under high rainfall, high leaching and well drainage favors kaolin formation. Hematite and goethite are also the products of intense weathering and being controlled mainly by redox conditions and pedoclimate.

Geochemistry of Soils on Nam Phong and Khon Buri Catenae

Major and minor elements in soils and their size fractions were determined by a combination of X-ray fluorescence spectrometry (XRF) analysis (Norrish and Hutton 1969) and aqua regia digestion (HCl and H_2CO_3) followed by inductively coupled plasma-mass spectrometry (ICP-MS) (Lynch 1999; Soltanpour *et al.* 1996). Aluminum, Si, Ti, Fe, Ca, Mg, K, Mn and Zr were determined by XRF on fused lithium tetraborate discs and P, Li, Cs, As, Cr, V, Ni, Rb, Cu, Zn, Ga, Co, Pb, Mo, Zr, U and Sr were analyzed by ICP-MS on a strong acid digest of finely ground soil, fine sand, and silt. For the clay fraction, Al, Si, Ti, Fe, Ca, Mg, K, Mn, P, Ni, Zr, Rb, Sr, Zn, Cu, Co, Cr, Ba and V were determined by XRF.

Element concentrations in soils are mainly related to the chemical composition of parent materials and to changes due to weathering which differ for various climatic environments (Duddy 1980; Topp *et al.* 1984). As soil profiles develop there is a redistribution of elements within the soil fabric, then between profile horizons and finally between soils within the landscape (Jenkins and Jones 1980). The spatial redistribution of elements during weathering is particularly complicated because elements are affected by various pedogenic processes including dissolution of primary minerals, formation of secondary minerals, redox processes, transport of material, and ion exchange (Chesworth *et al.* 1981; Fritz and Morhr 1984; Middleburg *et al.* 1988). Topography may also exert substantial control on elemental distribution in soils (Gallez *et al.* 1976). Under acid oxidizing conditions, Fe and Al remain whereas the Ca, Mg, Mn and Na move from upslope to the lower parts of the slope where alkaline conditions may prevail (Tardy *et al.* 1973). Birkeland (1999) proposed that elements released by weathering may or may not be redistributed along the slope as a function of their mobility in the constant or changing geochemical environments along the slope.

These multiple interaction processes result in complex patterns of element distribution in soil catenae which are not readily comprehended if data are presented in Tables or on multiple depth and landscape graphical representation. Multivariate statistical analyses studies are especially useful for assessing and depicting multiple chemical and physical variables of this type. Factor analysis, a widely used multivariate statistical method, was employed to interpret data. This technique reveals the correlation structure of the geochemical variables allowing the identification of affinity groups of elements and samples. The specific objectives of this part are to reports on the geochemistry of elements in the both catenae and test the hypothesis that there are elemental affinity groups for Thai soils that can provide a basis for describing the geochemical evolution of soils on the catenae.

The full analytical data for each size fraction comprise a large document which is not presented here however they are shown in Appendix I, Tables 9-16. Average concentrations of elements (mean and SD) in the whole soil, fine sand, silt and clay for Nam Phong and Khon Buri catena are given in Tables 7 and 8 respectively, to provide an indication of the concentrations of elements observed.

1. Geochemistry of Soils on Nam Phong Catena

The mean element concentrations for whole soil, fine sand, silt and clay fractions of each profile on the Nam Phong catena are given in Table 7. Silica is the major component in whole soils (439-362 g kg^{-1}) of all soils in this catena as would be expected on the basis of the sandy soil texture. Aluminum and Fe are minor constituents of soils at all positions with mean concentrations ranging from 2.9-65.2 and 2.6-38.1 g kg^{-1} respectively. Although different positions on the catena experience different intensity of weathering there is little difference in element concentrations in soils from summit to footslope but there is a substantial differences for toeslope soil.

2. Geochemistry of Soils on Khon Buri Catena

Summary of the chemical compositions of the soils on Khon Buri catena are provided in Table 8. All soils on Khon Buri catena contain much Al, Si and Fe with minor Ti and Mn. For soils on the upslope positions, the Al and Fe concentrations are larger than for the valley floor position reflecting a predominance of kaolin and iron oxide minerals upslope. The basic cations (Ca, K and Mg) are present in low concentrations in the soils on upslope positions especially for the crest soil, as is generally the case for Oxisols (Marques *et al.*, 2004a). The higher concentrations of Fe and Mn in soils on the footslope and in some horizons of soils on backslope positions are associated with the presence of Fe, Mn nodules (see Figure 44). Soils on the crest, backslope and footslope positions contain less Mg than does the weathered basalt as Mg is ready leached (Bulmer and Lavkulich, 1994). The valley floor soil contains high amounts of Si and basic cations reflecting the dominance of smectite. The higher concentrations of basic cations with depth might partly reflect the presence of primary minerals inherited from the parent rock. This interpretation is consistent with the presence of feldspar in silt and fine sand fractions. The high iron concentration in this soil which does not contain free iron oxides, is due to Fe being a component of smectite (Stucki, 1988).

Table 7 Average element concentrations [mean(SD)] in whole soils, fine sand, silt and clay fractions for Nam Phong catena

Element	Whole soil						Sand fraction					
	SU	SH	UM	LM	FS	TS	SU	SH	UM	LM	FS	TS
Si (g kg^{-1})	439(15)	446(14)	456(15)	446(9)	463(0.8)	362(39)	467(0.4)	467(0.3)	467(0.2)	466(0.4)	467(0.3)	441(27.6)
Al	22.7(12.1)	15.7(10.2)	6.9(7.1)	7.0(6.8)	2.9(0.6)	65.2(23.8)	0.7(0.1)	0.9(0.1)	1.0(0.1)	1.2(0.2)	0.8(0.1)	10.7(12.5)
Fe	10.9(5.3)	9.3(7.9)	7.0(12.8)	22.3(48)	2.6(0.7)	38.1(11.5)	0.1(0)	0.1(0.1)	0.1(0.1)	0.3(0.2)	0.7(0.4)	15.8(12.9)
Mg	0(0)	0(0)	0(0)	0.0(0.5)	0.0(0.3)	7.1(3.9)	0(0)	0(0)	0(0)	0(0)	0(0)	1.2(1.7)
Ca	0.2(0.1)	0.2(0.1)	0.1(0.1)	0.1(0)	0.1(0.1)	5.0(2.9)	0(0)	0(0)	0(0)	0(0)	0(0)	2.7(3.3)
K	0.6(0.3)	0.7(0.3)	0.5(0.4)	0.6(0.3)	0.4(0.1)	17.3(9.4)	0(0)	0(0)	0(0)	0(0)	0(0)	3(4)
Ti	1.8(0.4)	1.8(0.4)	1.3(0.1)	1.1(0.1)	0.9(0.1)	3.8(1.1)	0.3(0)	0.5(0)	0.6(0.1)	0.5(0.1)	0.4(0)	0.9(0.7)
Mn (mg kg^{-1})	33.3(12)	23.6(15)	20.5(25)	20.0(21)	20.1(20)	537(351)	1.3(0.5)	0.7(0.5)	1.9(0.5)	3.2(1.1)	1.9(1.7)	1810(216)
P	51.6(11.7)	46.8(28.1)	43.9(30.7)	97(92)	30.4(15.9)	82.9(71.5)	14.1(11.2)	5.2(5.2)	11.5(4.0)	24.3(3.8)	17.6(10.9)	298(252)
Zr	324(23)	434(120)	385(81)	270(79)	229(39)	318(71)	67(24)	101(28)	130(58)	136 (43)	48.5(27)	136(65)
Li	10.1(1.3)	5.1(2.6)	2.1(0.9)	0.8(0.7)	0.7(0.4)	29(17)	0.4(1.1)	1.3(1.1)	0(0)	0.6(0.7)	1(0.8)	3.5(4.2)
V	28.4(14.6)	26.4(21.3)	14.4(21.6)	26.8(47.5)	10.3(3.3)	40(16.4)	2.0(1.9)	1.8(3.2)	1.3(1.2)	2.9(2.8)	6.0(3.5)	25.3(11.5)
Cr	14.2(5.9)	44.3(87)	19.2(42.3)	55.5(123)	4.8(1)	31.1(13.3)	12.2(1.9)	10.7(4.1)	8.3(1.5)	10.1(3)	11.2(2.1)	22.6(4.5)
Co	0.5(0.1)	0.6(0.7)	0.5(0.8)	1.0(1.9)	0.2(0.1)	9.5(5.3)	0(0)	0(0)	0(0)	0(0)	0(0)	15.5(13.2)
Ni	28.2(8.2)	23.8(11.3)	24.9(16.1)	19.9(10.4)	27.5(9.9)	51.7(23.8)	1.0(0.5)	0.6(0.6)	1.2(1.3)	2.3(1.8)	1.3(1.7)	12.7(11.7)
Cu	4.6(2.1)	5.4(3.7)	3.1(3.6)	9.1(16.8)	1.4(0.4)	10.4(4.2)	3.3(1)	2.7(1.8)	1.4(0.3)	3.7(3.1)	1.5(0.2)	20(30.4)
Zn	22.3(8)	20.0(2.3)	15.9(6.2)	20.9(23.7)	12.2(5.3)	101.3(41.1)	4.7(1.3)	2.9(0.2)	3.1(0.6)	4.9(2.3)	3.1(0.6)	36.5(41.2)
Ga	4.9(2.2)	3.8(2.1)	2.2(1.3)	2.5(2.3)	1.3(0.2)	15(8)	0.2(0)	0.3(0.1)	0.4(0)	0.3(0.1)	0.4(0)	12.5(15.3)
As	3.0(1.5)	2.5(2.4)	1.5(2.5)	6.0(12.8)	0.8(0.3)	3(1.6)	0(0)	0.2(0.2)	0.2(0.2)	0.3(0.2)	0.4(0.3)	2.9(1.4)
Rb	10(3.9)	9.2(5.6)	5.3(3.3)	4.2(0.9)	3.0(0.7)	54(31.7)	0.6(0.2)	0.6(0.1)	0.9(0.1)	1.4(0.1)	0.7(0.1)	7.6(8.7)
Sr	2.9(0.6)	3.9(1.9)	3.4(2.1)	3.3(0.6)	1.9(0.1)	17.1(10.8)	0.3(0.2)	0.2(0.1)	0.5(0.1)	0.6(0.3)	0.2(0)	4.1(4.8)
Mo	1(0.7)	0.6(0.4)	0.4(0.4)	1.4(2.8)	0.3(0.2)	0.8(1)	0.1(0)	0.2(0.3)	0.1(0.1)	0.2(0.1)	0.2(0.1)	0.2(0.1)
Cs	2.1(0.8)	1.3(0.7)	0.6(0.3)	0.5(0.1)	0.3(0)	4.4(2.3)	0(0.1)	0(0)	0(0)	0(0)	0(0)	0.4(0.5)
Pb	12.3(4.2)	15.7(9.8)	12.8(10.1)	19.8(14.8)	8.9(1.3)	23.7(17.8)	1.9(0.3)	2.3(0.4)	2.9(0.3)	3.7(0.3)	3(0.1)	46.1(36.8)
U	0.2(0.1)	0.2(0.2)	0.2(0.2)	0.7(1.3)	0.2(0)	1.6(0.8)	0(0)	0(0)	0(0)	0(0)	0(0)	0.5(0.4)

Table 7 (Continued)

Element	Silt fraction						Clay fraction					
	SU	SH	UM	LM	FS	TS	SU	SH	UM	LM	FS	TS
Si	463(0.5)	464(1.1)	461(0.5)	461(1)	462 (0.6)	440(21)	232(10)	230(3)	236(7)	237(1.9)	249(3)	251(7)
Al (g kg^{-1})	2.2(0.2)	2.5(0.3)	2.8(0.1)	3.0(0.6)	2.5(0.4)	13.2(12.6)	192(8)	198(6)	190 (7)	186(4.1)	170(8)	157(10)
Fe	1.6(0.5)	1.9(0.7)	2.4(0.2)	2.6(0.4)	1.4(0.2)	12.3(7.8)	85.0(5)	77.5(7.2)	75.9(1.7)	74.5(1.1)	66.8(6)	65.4(5.3)
Mg	0(0)	0(0)	0(0)	0(0)	0(0)	1.3(2)	1.9(0.4)	2.6(0.3)	2.8(0.4)	3.8(0.2)	7.9(0.6)	13.9(2.7)
Ca	0.1(0)	0.2(0)	0.1(0)	0.2(0)	0.2(0)	0.9(0.8)	0.3(0.4)	0.7(0.7)	0.6(0.7)	0.7(0.6)	1.0(0.4)	0.6(0.4)
K	0.2(0)	0.4(0.2)	0.5(0)	0.5(0)	0.8(0.4)	3.7(3.6)	5.1(0.3)	6.8(0.2)	8.1(0.3)	10.3(1.2)	18.5(1.3)	31.5(7.2)
Ti	3.2(0.4)	3.5(0.4)	3.7(0.6)	3.5(0.2)	3.3(0.1)	4.5(0.7)	5.9(1.9)	4.1(0.5)	4.7(1.2)	4(0.3)	4.4(0.7)	2.8(0.6)
Mn (mg kg^{-1})	12.1(5.2)	9.4(1.2)	14.0(4.5)	10.9(4)	9.1(4.3)	151(105)	0.4(0.3)	0.3(0.3)	0.4(0.2)	0.4(0.2)	0.7(0.9)	1.3(1)
P	14.8(6.2)	14.2(7.4)	20.5(7.4)	28.8(5.3)	12.4(4)	94(146)	5.4(1.2)	7.1(2.5)	8.7(2.9)	12.6(3.4)	6.6(2.6)	1.7(1.4)
Zr	660(154)	756(331)	563(139)	650(148)	999(444)	742(305)	176(20)	150(13)	152(24)	143(18)	148(21)	109(9)
Li	0.8(0.9)	0.9(0.8)	0.9(1)	0.0(0.1)	0.7(0.4)	5.3(6.4)	nd	nd	nd	nd	nd	nd
V	4.0(0.9)	5.7(2.7)	5.5(0.9)	8.4(2.1)	5.7(1.6)	15.5(8.1)	212(21)	205(27)	195(24)	182(7.5)	171(9.5)	112(26)
Cr	3.7(1.1)	2.8(1.1)	2.6(0.7)	3.7(1.3)	4.1(4.2)	10.3(5.7)	88 (9.3)	100(7)	96(6.4)	85(11.3)	91(30.1)	78(10)
Co	0.1(0.1)	0.1(0)	0.1(0)	0.1(0)	0.1(0)	2.9(2.4)	1.5(13.1)	7.7(14)	12.5(7.3)	11.7(10)	15.5(8.4)	30.8(16.4)
Ni	0.7(0.2)	0.4(0.1)	0.4(0.1)	0.5(0.2)	0.5(0.2)	8.0(8.2)	15.5(3.7)	15.3(6.5)	6.8(3.6)	8.7(8.1)	19.3(9.6)	38.8(8.2)
Cu	1.1(0.3)	1.0(0.3)	1.4(0.3)	1.5(0.4)	0.9(0.1)	4.0(3.1)	31.3(14.7)	33.3(2.9)	41.3(8.4)	47.3(15.3)	53.3(10.8)	26.6(6.4)
Zn	15.3(5.4)	9.7(1.2)	11(6.6)	16.9(4.6)	11(6.7)	40(16)	142(99)	132(42)	145(56)	176(105)	243(92)	163(27)
Ga	0.3(0.1)	0.4(0.1)	0.5(0.1)	0.5(0.1)	0.4(0)	2.9(2.8)	nd	nd	nd	nd	nd	nd
As	0.2(0.2)	0.1(0.1)	0.2(0.1)	0.5(0.3)	0.2(0.1)	1.1(0.5)	nd	nd	nd	nd	nd	nd
Rb	1.4(0.4)	1.8(0.2)	2.2(0.2)	2.1(0.2)	1.6(0.1)	8.4(8.9)	93.5(8.5)	122(9.6)	142.3(5.7)	158.7(11.4)	183.8(10.9)	223.8(13.1)
Sr	0.5(0.2)	0.6(0.2)	0.8(0.3)	1.6(0.9)	0.6(0)	4.0(3.9)	31.5(3.8)	38.7(2.3)	31(7.2)	41(5.2)	50(7.5)	23.6(7.4)
Mo	0.1(0)	0.2(0.1)	0.1(0)	0.2(0.1)	0.1(0.1)	0.1(0)	nd	nd	nd	nd	nd	nd
Cs	0.4(0)	0.3(0)	0.3(0)	0.3(0)	0.2(0)	0.7(0.7)	nd	nd	nd	nd	nd	nd
Pb	1.9(0.5)	2.7(0.9)	3.6(0.6)	6.7(3)	4.2(0.4)	9.4(5)	nd	nd	nd	nd	nd	nd
U	0.1(0)	0.1(0)	0.1(0)	0.1(0)	0.1(0)	0.5(0.2)	nd	nd	nd	nd	nd	nd

SU = Summit, SH = Shoulder, UM = Upper midslope, LM = Lower midslope, FS = Footslope, TS = Toeslope; nd = not detemined

<u>Table 8</u> Average concentrations [mean(SD)] in the whole soil, fine sand, silt and clay fractions for Khon Buri catena

Element	Whole soil				Sand fraction				Silt fraction				Clay fraction			
(g kg^{-1})	CT	BS	FS	VF	CT	BS	FS	VF	CT	BS	FS	VF	CT	BS	FS	VF
Si	225(4)	220(3)	226(5)	290(18)	443(5)	293(15)	337(26)	375(42)	287(27)	226(26)	283(18)	384(26)	192(1.6)	215(3)	212(5)	250(15)
Al	157(6)	151(19)	120(24)	94(15)	10(2.5)	56(15)	27(7)	28(15)	75(18)	81(27)	401(15)	28(9)	192(0.3	203(4)	185(5)	138(21)
Fe	125(0.5)	140(17)	176(30)	100(11)	21(2.5)	172(9.9)	147(27)	76(43)	118(19)	201(24)	161(12)	59(24)	130(1.4)	86(7)	116(11)	108(3)
Mn	8.4(2.0)	14(6.2)	26(11)	17(3.2)	4.4(2.1)	13(2.7)	27(32)	38(26)	7.3(1.6)	11(6.2)	11(4)	7.8(2.9)	0.81(0.1)	0.67(0.3)	0.95(0.3)	1.4(0.3)
Mg	1.21(0.3)	1.9(0.5)	2.1(0.4)	8.5(2.9)	0(0)	1.2(0.2)	1.02(1)	2.6(0.6)	2(0.3)	2.4(0)	2.7(0)	2(0.2)	0.85(0.1)	1.3(0.1)	2(0.2)	9.9(5)
Ca	0.24(0.2)	1.5(1)	0.89(1.2)	8.3(4.2)	0.2(0.1)	0.70(0.4)	0.36(0.2)	9.1(7.8)	0.20(0.1)	1.0(0.7)	0.60(0.6)	3.7(1)	0(0)	0.29(0.1)	0.15(0.1)	4.3(3)
K	0.66(0)	1.3(0.4)	1.6(0.1)	1.1(0.3)	0(0)	0.16(0.1)	0.05(0.1)	0.3(0.3)	0.58(0.1)	0.92(0.1)	1.9(1)	2.1(0.3)	0.58(0)	0.89(0.2)	1.6(0.3)	0.57(0.3)
Ti	24(0.4)	22(2.6)	18(1.3)	19(3)	2.3(0.4)	6.7(1.5)	4(1.5)	5(2.5)	41(6)	40(4)	45(3)	22(3.3)	21(1.3)	17(1.8)	13(0.3)	13(3)
(mg kg^{-1})																
P	378(74)	470(122)	544(335)	123(111)	251(60)	1692(163)	1707(635)	1401(872)	120(57)	327(109)	202(118)	71(111)	6.50(1.3)	4.8(2)	5.2(3.2)	1.8(2.2)
Zr	537(22)	434(71)	469(41)	382(27)	227(36)	284(29)	295(111)	177(49)	1366(252)	978(138)	1121(249)	676(73)	286(16)	223(28)	181(6)	179(41)
Li	19(2.5)	20(3.9)	13.2(4.9)	12(1.4)	0.5(0.6)	4.4(1.6)	0.88(1)	0.98(1.1)	7.3(3.7)	7.9(5.1)	2.1(1.2)	0.75(0.7)	nd	nd	nd	nd
V	201(7)	235(29)	311(80)	200(28)	60(5)	294(33)	253(35)	173(88)	135(18)	257(42)	219(36)	91(39)	241(12)	162(16)	185(29)	207(62)
Cr	231(29)	200(25)	354(160)	170(40)	261(15)	320(31)	325(65)	131(35)	118(10)	150(25)	216(52)	84(26)	139(1)	89(8)	129(9)	186(36)
Co	27(7)	44(11)	80(25)	46(5)	26(9.8)	36(13)	83(76)	77(57)	21(5)	33(10)	43(9)	21(10)	52(7)	54(10)	64(19)	63(10)
Ni	54(5)	103(32)	147(18)	84(4)	10(3.6)	56(3)	67(29)	55(19)	29(6)	64(6)	66(21)	33(13)	159(8)	185(5)	187(6)	120(13)
Cu	36(1)	59(9)	76(7)	45(4)	10(7.6)	54(6)	54(20)	30(14)	31(3)	63(11)	55(11)	30(3)	68(7)	61(8)	80(12)	55(8)
Zn	37(2)	65(11)	74(8)	50(7)	13(3)	49(6)	48(19)	33(19)	39(4)	60(11)	55(8)	28(12)	100(13)	100(18)	88(2)	88(19)
Ga	22(1)	30(4)	36(8)	20(2.5)	4.5(0.6)	21(2)	23(15)	12(6)	13(1.9)	21(2)	15(2)	6.2(3.3)	nd	nd	nd	nd
As	1.4(0.2)	1.5(0.2)	2.6(1.3)	0.5(0.3)	0.84(0.4)	4.7(0.2)	4.4(0.4)	4.4(1.8)	0.25(0.1)	0.97(0.1)	0.85(0.3)	0.35(0.3)	nd	nd	nd	nd
Rb	4.5(0.5)	14(5)	24(6)	7.7(2.3)	0.28(0.2)	1.8(0.5)	1.5(0.2)	1.8(1.4)	2.2(0.5)	4.1(1.4)	2.9(0.4)	1.4(0.7)	nd	nd	nd	nd
Sr	5(1.1)	21(11)	9.7(9.6)	80(29)	1.3(0.7)	6.7(3.2)	3.0(1.6)	54(34)	2.6(0.7)	12(8.3)	4(4.7)	22(3.3)	21(4.6)	27(5.6)	40(8)	19(6)
Mo	2(0.3)	1.7(0.2)	1.5(0.6)	0.41(0.3)	0.72(0.1)	2.1(0.4)	1.4(0.3)	0.90(0.5)	0.62(0.3)	1.4(0.1)	0.93(0)	0.24(0.2)	12(7.5)	16(11)	6(7)	37(24)
Cs	1.8(0.1)	1.5(0.2)	1.6(0.5)	0.85(0.2)	0.05(0)	0.17(0.1)	0.04(0)	0.11(0.1)	0.84(0.1)	0.57(0.3)	0.28(0)	0.20(0.1)	nd	nd	nd	nd
Pb	9.5(0.5)	8.8(1.9)	12(5.1)	9.1(0.9)	8.23(1)	12(1.5)	10(6)	16(11)	5.1(0.8)	7.2(1.7)	5.4(2.9)	8.1(2.3)	nd	nd	nd	nd
U	0.39(0)	0.49(0.1)	0.5(0.1)	0.56(0.3)	0.04(0.1)	0.30(0.1)	0.12(0.1)	0.17(0.1)	0.27(0)	0.51(0.1)	0.33(0.1)	0.30(0.2)	nd	nd	nd	nd

CT = crest, BS = backslope, FS = footslope, VF = valley floor, nd = not determined

Minor element concentrations of soils on this catena are in the same range as other basalt derived soils as reported by Alloway (1995) (Appendix I, Table 13). The Zr concentration in soils at all positions is quite uniform possibly due to Zr being maintained in soils in the form of zircon which is extremely resistant to weathering (Sudom and Arnaud, 1971). The minor element distribution patterns differ between soil profiles at different catenary positions. This is interpreted as being partly due to different concentration of elements in parent rock across the profile, partly to the effects of pedogenesis and there is a possibility of minor amounts of introduced authigenic synthesis (Eswaran, 1971). Amounts of residual elements are expected to be high in soils on the crest, backslope and footslope positions where a strongweathering condition occurs. Conversely, in the case of the valley floor soil where leached ions accumulate and precipitate as smectite and carbonates, there will be an accumulation of mobile elements (Harder, 1972; Tardy *et al.*, 1973).

A large data set such as this cannot be coherently interpreted by considering the within and between profile trends in element concentration on an element-by-element basis. It is necessary to use statistical techniques of data analysis and hypothesis testing as is described in the following section.

3. Soil Chemical Composition Changes along the Catenae

Factor analysis was used to determine elements of similar geochemical behavior and also to group soil samples on the basis of their geochemical affinity (Weber and Davis, 1990; Bellehumeur *et al.*, 1994). In this study, factor analysis of standardized data was used to identify relationships between the various components (elements) for the soils on both catenae.

For Nam Phong catena, Figure 27 showing that two factors represent 83 percent of the total data variability for analysis of whole soil. There are four groups of elements of similar behavior in Nam Phong catena (Figure 27a). The first group (Fe group) is composed of Fe, As, Cr, Mo, Cu, V, Pb, P, and U, the second group (Al group) is Al, Mn, Co, Ca, Mg, K, Sr, Cs, Rb, Ga, Zn, Ni, Li and Ti, the third group is

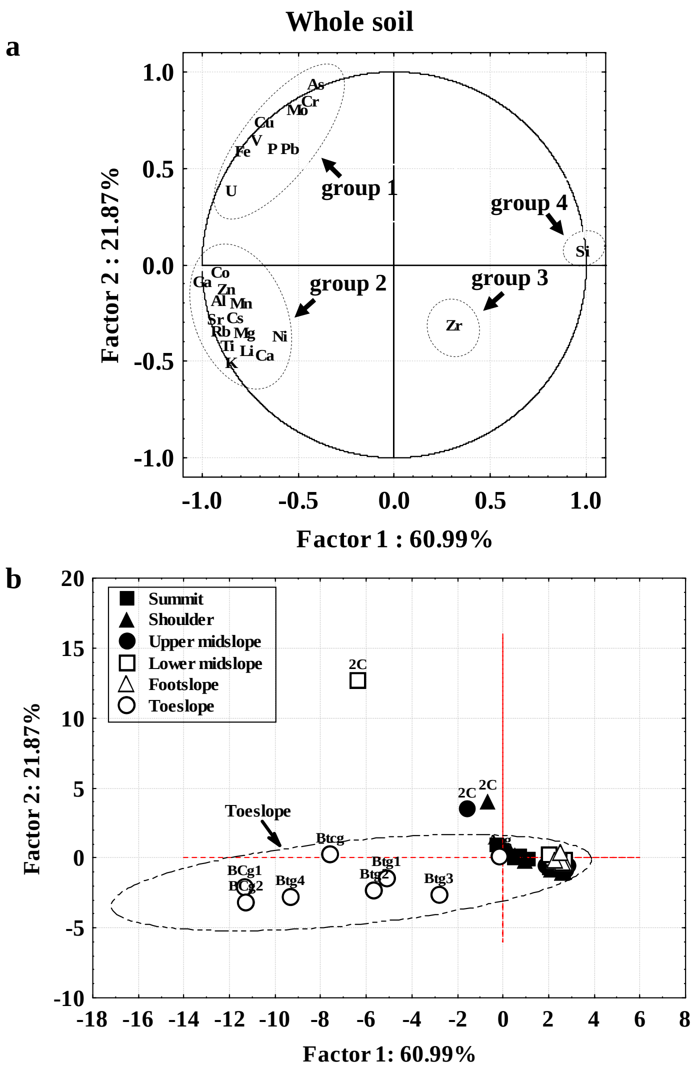


Figure 27 Factor analysis for element concentrations in whole soils of Nam Phong catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clarity. The 2C-horizon of the soil on shoulder, upper midslope and lower midslope are different from the remaining samples (b) indicating discontinuity within the profile.

Zr and the last group is Si. The metals in the iron group can substitute in Fe oxides as they have ionic properties that are compatible with Fe oxide structures (Farrah and Pickering 1979). Arsenic and P occurs in this group as they exist in soils as oxyanions that are strongly adsorbed by Fe oxides. The Al, Mn- group represents clay minerals and manganese oxides together with elements that are compatible with these minerals (Dolcater *et al.* 1970; Kinniburgh *et al.* 1976; Kabata-Pendias and Pendias 2001). Soils from the summit to the footslope are uniform in composition except some 2C-horizon of the shoulder and midslope soils (Figure 27b), which attribute a discontinuity of parent material within the soil profile possibly the presence of a veneer of colluvium. The soil on the toeslope is distinctly different from the other soils as exhibits considerably diversity between horizons.

Results of factor analysis of standardized element concentrations in whole soils for Khon Buri catena are given in Figures 28a and 28b. Two factors explain 72 percent of the variation in the data. Elements can be allocated to three main groups of similar geochemical behavior, with other elements not belonging to any group. The first group is composed of Al, Ti, Li, Zr, Cs and Mo. Titanium, Zr and Al are classed as residual elements in soils and are highly resistant to removal by weathering (Sudom and Arnaud, 1971; Cornu *et al.*, 1999; Stiles *et al.*, 2003). The reason for Mo, Cs and Li being in this group are unknown as these elements can be classified as mobile (Korte *et al.*, 1976; Kabata-Pendias and Pendias, 2001). The second group is Fe, Mn, P, Ga, Cr, Pb, Rb, V, Cu, Zn, Ni, Co, K and As. Many metals are associated with Fe as members of the secondary oxide group as the metals can substitute for Fe in oxide structure (Kabata-Pendias and Pendias, 2001), with P and As belonging to the group as they form strongly adsorbed anions (Fontes and Weed, 1996). The third group is Ca, Si, Sr and Mg. Silicon, Ca and Mg are elements that are most abundant in the alkali and smectite rich valley floor soil.

Soil on the crest has a very uniform element compositions throughout the profile as is indicated by the tight grouping of samples in the factor plot whereas the soils on backslope, footslope and valley floor show more diversity in composition (Figure 28b). The crest and valley floor soils are distinctly different whereas backslope and footslope soils are quite different but do overlap with each other to some extent.

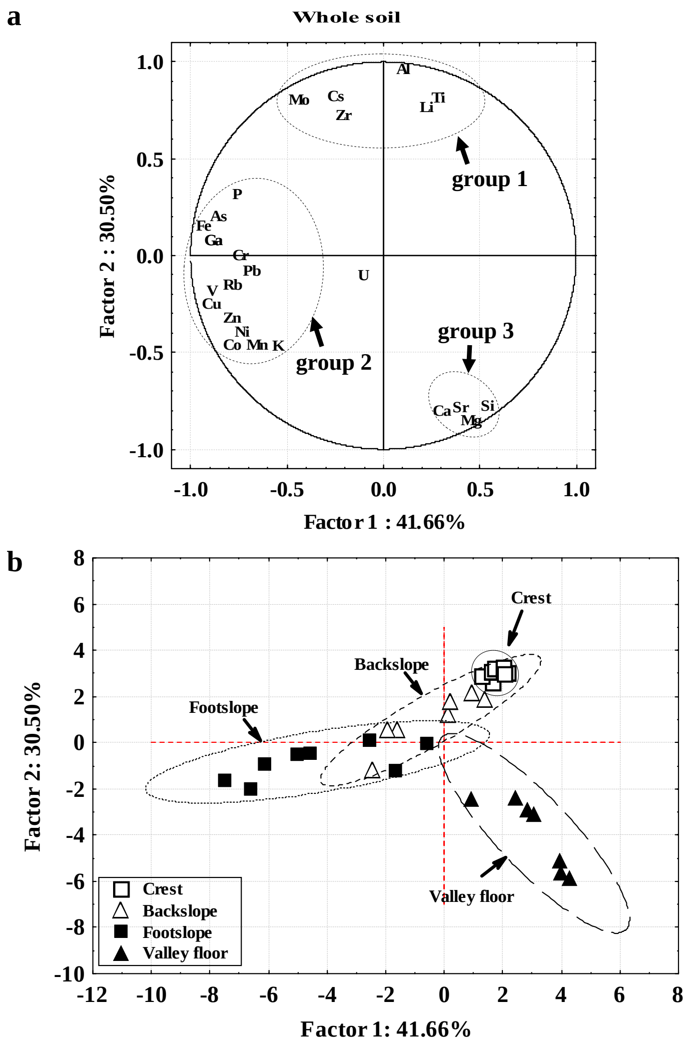


Figure 28 Factor analysis for element concentrations in whole soils of the Khon Buri catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clarity.

4. Geochemistry of the Fine Earth Fractions for Both Catenae

4.1 Distribution of Elements in the Fine Sand Fraction

Factor analysis of the element concentrations in the fine sand fraction for Nam Phong catena (Figure 29a) shows that two factors describe 89 percent of the variation in the total data set. Two distinct groups with similar elemental behaviors are recognized. The first group is solely Si, the second (Al group) with an opposite

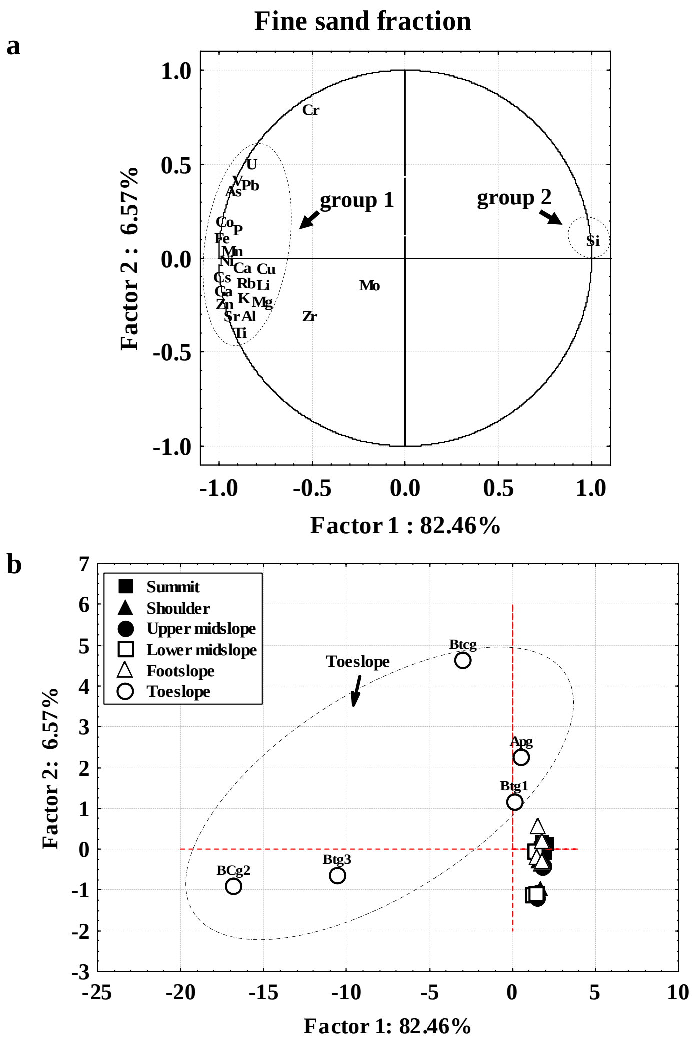


Figure 29 Factor analysis for element concentrations in fine sand fraction of the Nam Phong catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clarity.

relationship to Si comprise all the remaining elements with Cr, Zr, Mn falling slightly outside this group. Thus the groupings represent Si in quartz sand grains and the other elements in various silicate and oxide grains including sand size soil concretions. Soils from the summit to footslope overlap closely (Figure 29b). Sand in the toeslope shows large variation composition and is distinctly different from that in the other soils.

For Khon Buri catena, the factor analysis of the element concentration in the fine sand fraction (Figure 30) shows that about 73 percent of the variation in the data

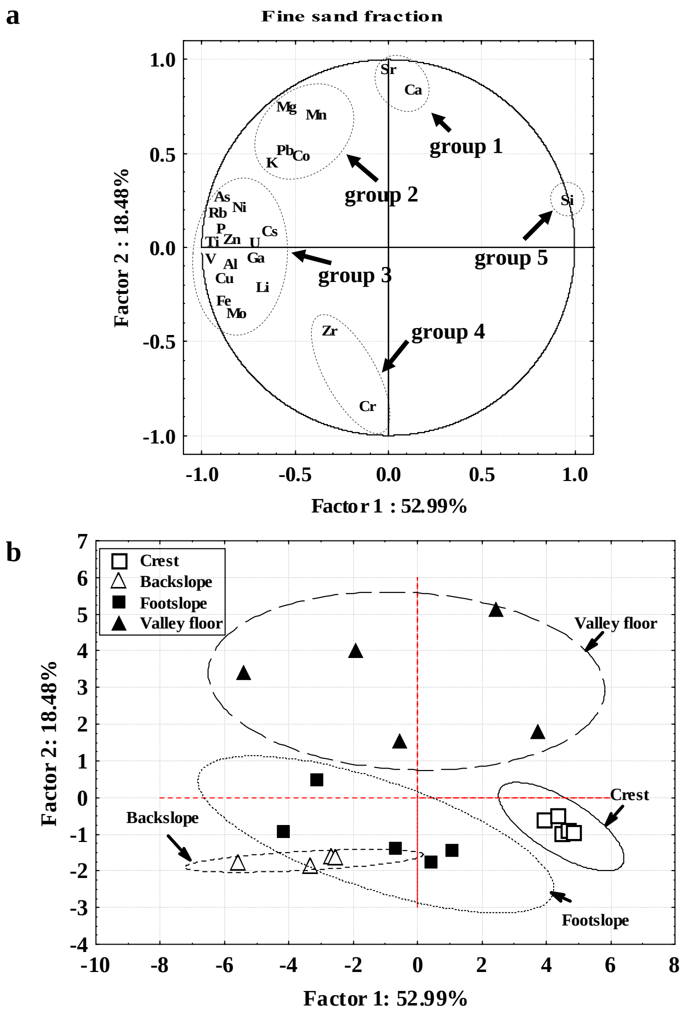


Figure 30 Factor analysis for element concentrations in the fine sand fraction of Khon Buri catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) t they have been slightly displaced for clarity.

is explained by two factors. Elements of similar elemental behaviors in the fine sand fraction are grouped together in Figure 30a. The first group composes of Ca and Sr, the second group is Mn, Mg, Pb, Co, and K, the third group is Fe, Rb, Ni, P, U, Zn, Ga, V, Al, Cu, As, Ti, Cs, Li and Mo, the fourth group is Zr and Cr and the last group is Si. Vanadium and Ni are frequently associated with Fe as these elements form structural analogues to goethite and hematite, and thus readily substitute for Fe in natural hematite and goethite (Singh and Gilkes, 1992c: Schwertman and Pfab, 1996). Iron and P are positively related as is commonly observed for basalt derived soils (Marques *et al.*, 2004b) due to P being sorbed by sand sized iron oxide aggregates.

The soil on the crest has the most uniform chemical composition and is distinctly different from soils at other positions. The soil on the backslope is quite uniform, whereas the footslope soil has a quite diverse element composition which overlaps with that of the backslope soil. The soil horizons of the valley floor soil have highly diverse compositions and this soil differs from the other soils (Figure 30b) on the basis of its fine sand composition.

4.2 Distribution of Elements in the Silt Fraction

Three groups of elements of similar behavior occur in the silt fraction of the soils on Nam Phong catena and describe 84 percent of the variation in the data set, these groups are the same groups as for fine sand fraction (Figure 31a). The first group is Si representing quartz, and the second is Zr representing zircon and the last group (Al group) is most other elements (Al, Cs, Sr, Rb, As, Ga, Cu, Ni, Co, Cr, V, Li, P, Mn, Mg, K, Ca, Fe, As Ti, Pb, U and Zn) which are quite widely distributed. The soils from the summit to footslope position show little variation in composition (Figure 31b). The toeslope soil shows a large variation in the chemical composition and is distinctly different from the other soils.

For Khon Buri catena, four groups of elements with similar behavior in the silt fraction are shown in Figure 32a and two factors explain 74 percent of the variation between the samples (Figures 32a and 32b). The first group is Si, the second group is Ca, Sr, K and Pb, the third group is Fe, Mn, P, Co, U, As, Ni, Cu, Cr, Mg, V, Zn, Mo, Rb, Ga and Cd, the last group is Ti, Al, Li, Zr and Cs. Titanium may substitute for Al and Si in clay minerals (Dolcater *et al.*, 1970; Fitzpatrick and Le Roux, 1977) but much Ti is present as anatase, rutile and ilmenite grains. Silt in the crest soil has a small range in element compositions whereas the soils on backslope, footslope and valley floor have moderate ranges in chemical composition but no soils on this catena do compositions of silt overlap (Figure 32b).

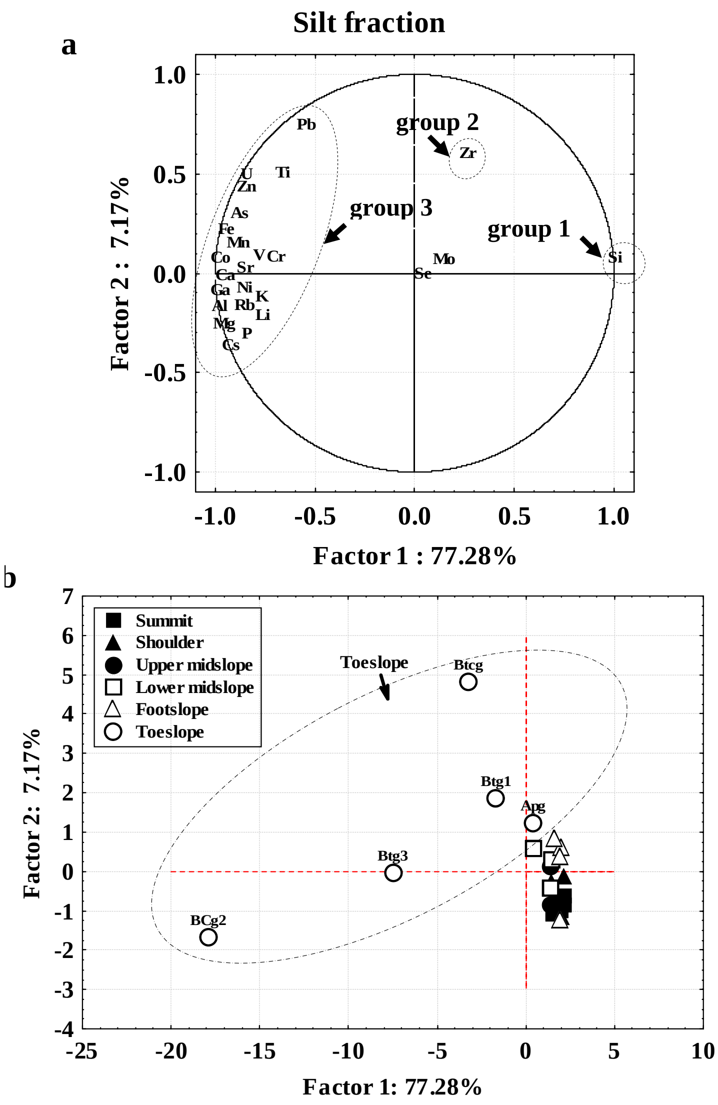


Figure 31 Factor analysis for element concentrations in silt fraction of Nam Phong catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clarity.

4.3 Distribution of Elements in the Clay Fraction

For Nam Phong catena, Figure 33a shows that two factors represent 65 percent of the total data variability. Three groups of element with different behaviors are indicated. The first group is Si, Ni, Mn, Co, Mg, K, Ba and Pb, the second group is Al, Fe, Zr, Ti and V, and the last group is Ca, Zn, Cu, Sr, Cr and P. There are no simple mineralogical explanations for these groupings which is probably a consequence

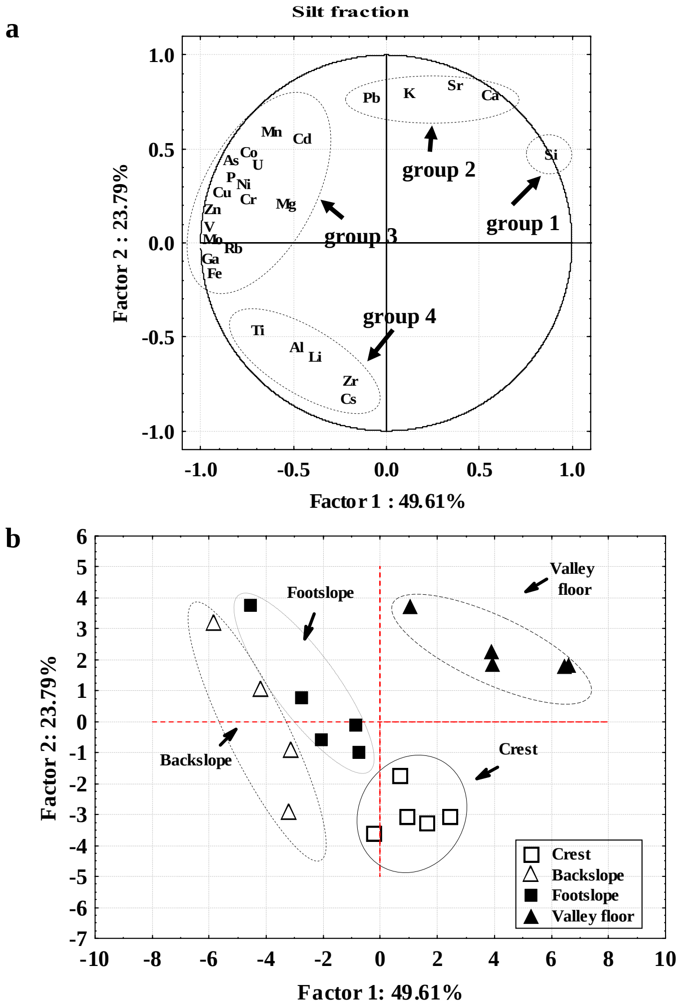


Figure 32 Factor analysis for element concentrations in the silt fraction of Khon Buri catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clarity.

of the diverse and complex mineralogy of the clay fraction that contains several clay minerals, oxides and sesquioxides with diverse association of elements, for example Mn, Co, Ni, Ba, Pb and K may be associated in manganese oxide minerals (Kabata-Pendias and Pendias, 2001). All soils on this catena show moderate within profile variation in element composition and are quite widely dispersed in Figure 33b. The footslope soil is distinctly different as is the toeslope profile with much Ni, K, Mg and less Pb, Co and Ba. The compositions of clay in summit, shoulder and midslope soils are diverse and overlap to some extent.

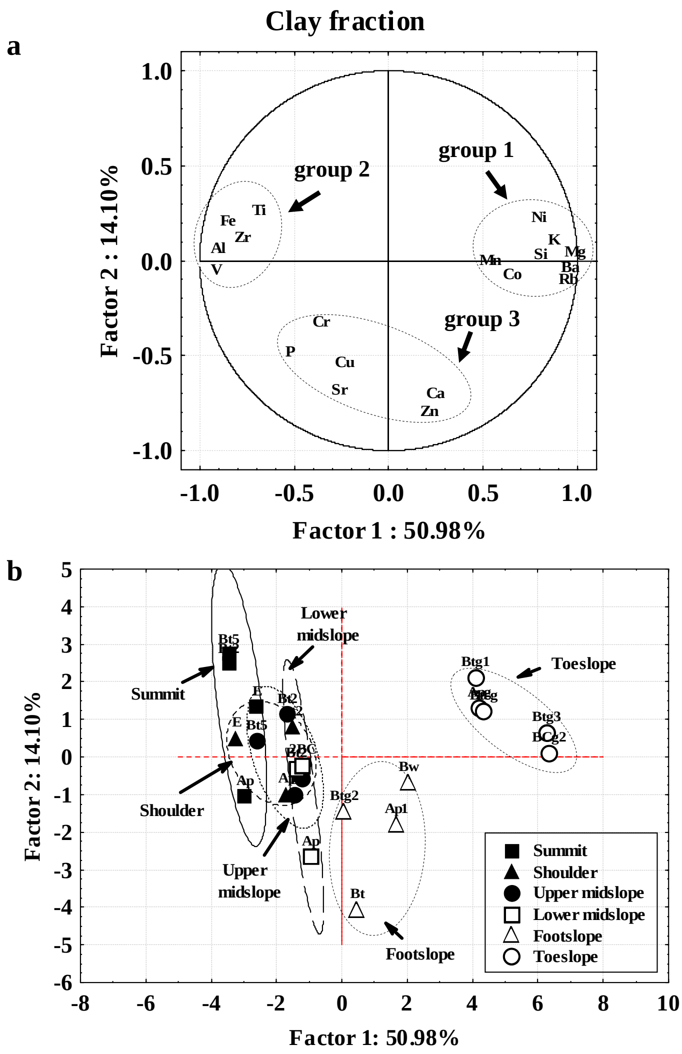


Figure 33 Factor analysis for element concentrations in clay fraction of Nam Phong catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clarity.

For Khon Buri catena, the factor analysis (Figures 34a and 34b) shows that 64 percent of the variation in the geochemical data for the clay is explained by two factors. There is only one group of elements exhibiting similar behavior which includes Mg, Sr, Ca, Cr, Mn and Si, other elements are quite widely distributed. The single group consists of elements that are leached from the upslope soils and accumulate in the valley floor during pedogenesis. Cr is also included in this group but usually has different affinities although Cr can occur in structure of smectites and

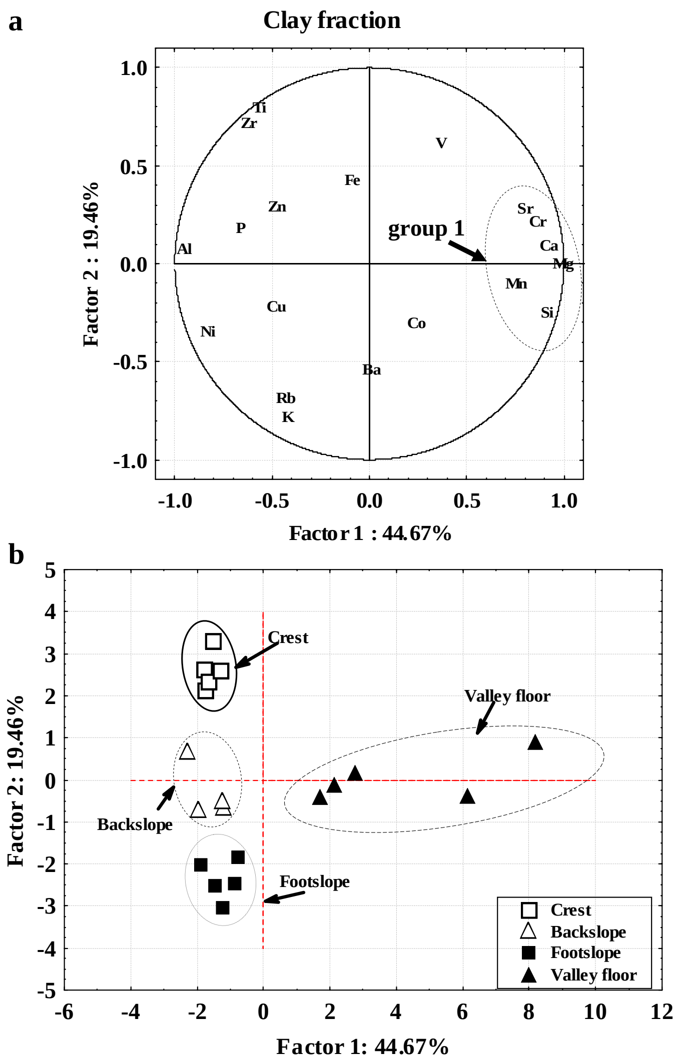


Figure 34 Factor analysis for element concentrations in the clay fraction of Khon Buri catena: (a) distribution of elements; (b) distribution of soil samples, where elements were superimposed in (a) they have been slightly displaced for clearly.

other clay minerals (Newman, 1987). The clay in crest, backslope and footslope positions shows little variation in composition between soil horizons and the soil on the valley floor exhibits moderate variation. The clay in all four soils on this catena has quite distinct compositions in each profile (Figure 34b).

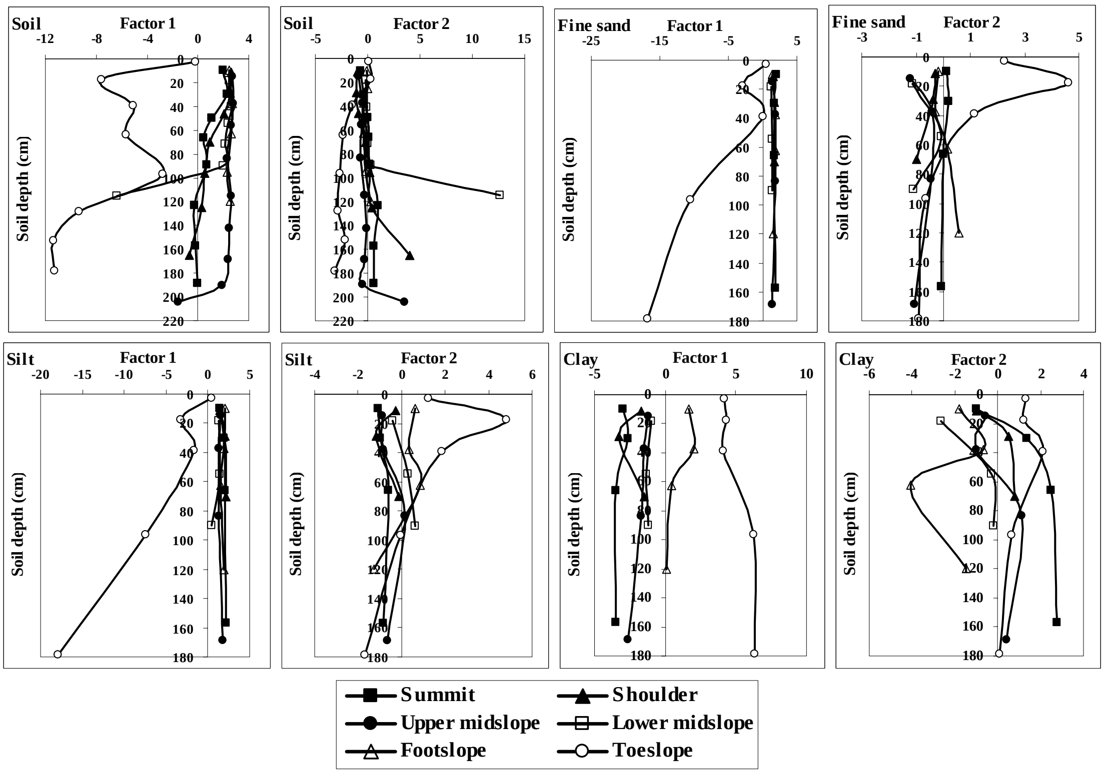
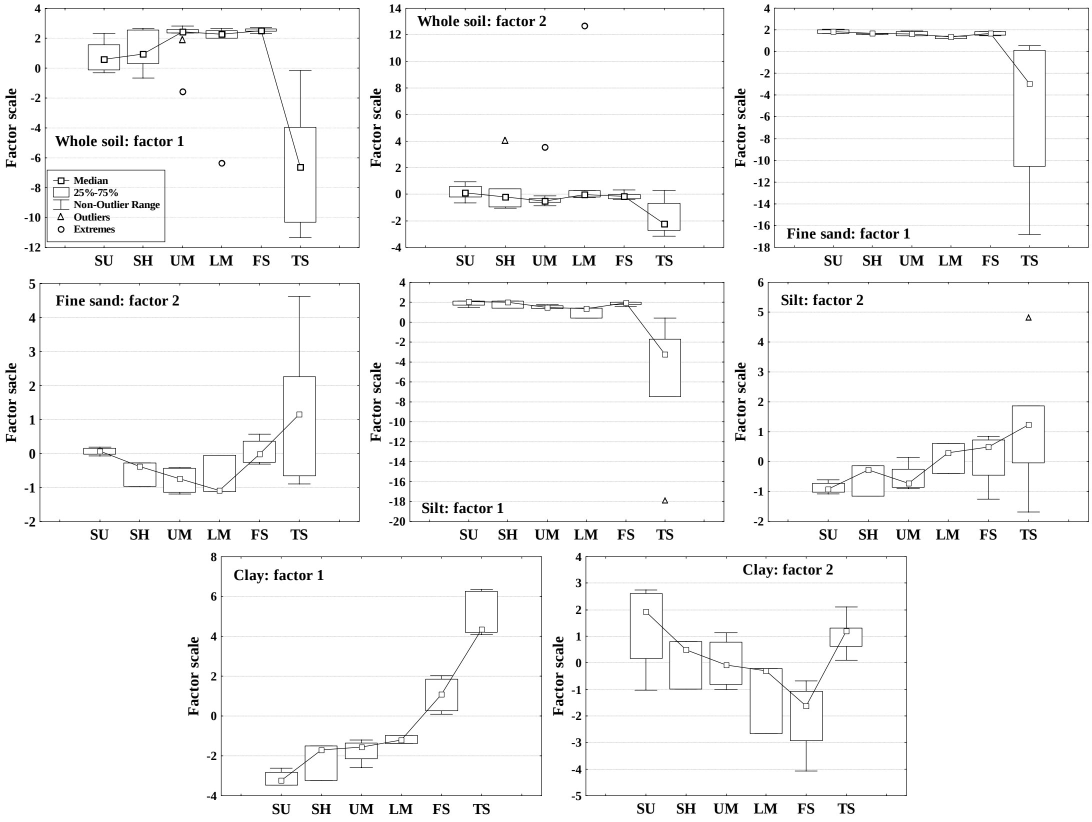


Figure 35 Depth functions for factors 1 and 2 for the whole soil, fine sand, silt and clay fractions of Nam Phong catena. Note that composition of the two factors differ for the few sample types.

5. Depth and Landscape Variations in Chemical Composition on Nam Phong Catena

Depth functions of mean factor 1 and 2 scores for element concentrations in the whole soils, fine sand, silt and clay fractions for each profile of Khon Buri catena are given in Figure 35. Factor 1 and factor 2 for the soils on the summit, shoulder, midslope and footslope are quite uniform with depth for all fractions except for the factor 2 for silt and factor 1 for clay. For the toeslope soil, factor 1 decreases with depth to negative values for the whole soil, fine sand and silt and is positive and constant with increasing depth for the clay. Factor 2 tends to show negative values with depth for the sand and silt and show no clear trend with depth for the whole soil and clay for any profile.



SU: summit, SH: shoulder, UM: upper midslope, LM: lower midslope, FS: footslope, TS: toeslope

Figure 36 Spatial variation in profile mean values of factors 1 and 2 for soil, fine sand, silt and clay fractions for Nam Phong catena. Note that composition of the two factors differ for the few sample types.

The spatial variation in mean factor values for profiles (mean values of factors 1 and 2) along the catena transect are shown in Figure 36. For the whole soil, factor 1 (Fe group) and factor 2 (Si) are uniform from the summit to footslope soils and becomes much smaller for the toeslope soil. For fine sand and silt, factor 1 (Si group) is constant from the summit to footslope and much smaller for the toeslope soil. There are no systematic trends with position for factor 2 (Al group) for the fine sand whereas factor 2 (Al group) exhibits a gradual increase downslope for silt. For clay, factor 1 (Al group) increases systematically downslope but factor 2 (Ca group) decreases from summit to footslope soil and increases for the toeslope.

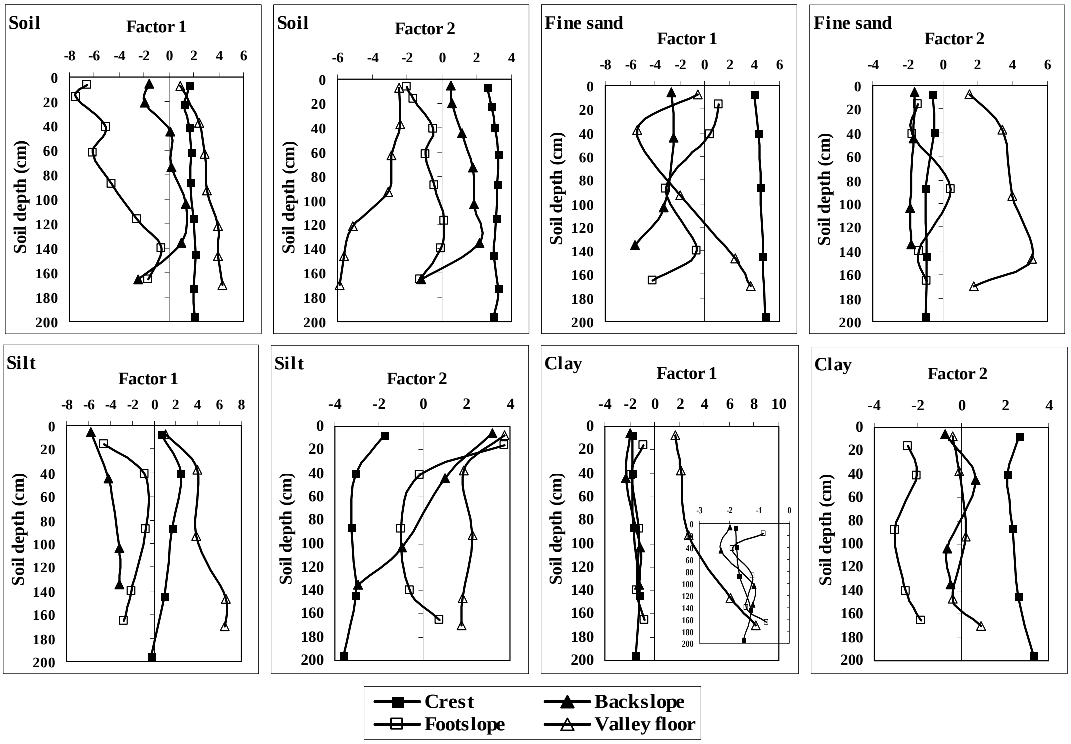
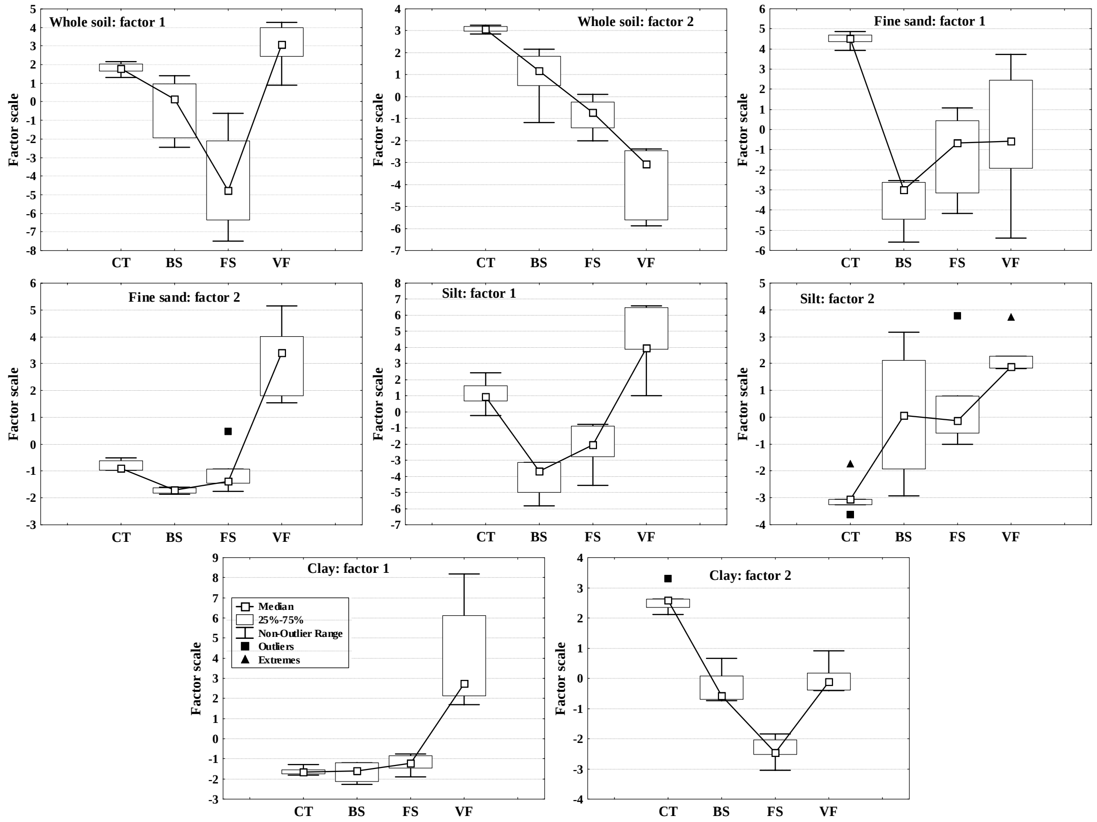


Figure 37 Depth functions for factors 1 and 2 for the whole soil, fine sand, silt and clay fractions of Khon Buri catena. Note that composition of the two factors differ for the few sample types.

6. Depth and Landscape Variations in Chemical Composition on Khon Buri Catena

Depth functions of mean factor scores for element concentrations in the whole soils, fine sand, silt and clay fractions for Khon Buri catena are given in Figure 37. For the whole soils, factor 1 is constant with depth for the crest, backslope and valley floor profiles and become less negative with depth for the footslope profile, mostly reflecting decreasing amount of Fe with its associated elements and Ca with depth (Figure 28a). Factor 2 is quite uniform with depth for crest, backslope and footslope profiles and becomes more negative with depth for the valley floor soil as Ca, Mg and Sr concentrations increase and there is less Al and Ti. For the fine sand fraction neither factor shows a systematic trend with depth. For the silt fraction, factor 1 is quite uniform with depth for all soils. Factor 2 for the backslope and footslope soils becomes negative with depth due mostly to changes in concentrations of Ti, Al, Li, Zr and Cs. For the clay fraction, factor 1 is uniform with depth and is negative for the



CT: Crest, BS: Backslope, FS: Footslope, VF: Valley floor

Figure 38 Spatial variation in profile mean values of factors 1 and 2 for soil, fine sand, silt and clay fractions for the Khon Buri catena Note that composition of the two factors differ for the few sample types.

soils on the crest, backslope and footslope and becomes highly positive with increasing depth for the valley floor where there is more Mg, Ca, Cr and Sr. Factor 2 for clay is quite uniform with depth for the soils at all positions.

The spatial variation in mean factors values for profiles (mean values of factors 1 and 2) along the catena transect are shown in Figure 38. For the whole soil, factor 1 (Fe group of elements) decreases downslope and become high for the valley floor soil whereas factor 2 (Si(-), Al(+), Ti(+)) decreases systematically downslope for the four profiles. For fine sand, there are no systematic trends with position for factors 1 or 2. Factor 1 for silt shows no systematic trend with position whereas factor 2 increases systematically downslope. For clay, factor 1 (Ca(+), Mg(+), etc) increases downslope but there is not a systematic trend for factor 2.

7. Distribution of Elements Between Size Fractions on Nam Phong Catena

The relative contributions of fine sand, silt and clay fractions to the chemical composition of the soils on Khon Buri catena are shown in triangle graphs (Figure 39). Note that coarser sand fractions are not included within this diagram and for most elements will contribute elements in a similar manner to fine sand but generally at lower concentrations (Darmody 1985; Chatupa and Direng 2000). Aluminum, Fe, K, Mg, Ca, Co, Rb, Zn and Sr are associated with the clay fraction for most of soils except that Al, Zn and Fe are contributed by silt and sand for the footslope soil. The contributions of minor elements are generally high for the clay fraction as has been reported by other workers (Song *et al.* 1999). Silicon and P are strongly associated with the sand fraction reflecting the abundance of quartz and possibly the presence of apatite grains (Ca, P) in the silt and sand. In the toeslope soil, Si and Ca are contributed by all three fractions. Cr, Cu, Ni and V are contributed mostly by the sand and clay. Titanium is contributed by all size fractions however it tends to mostly be present in the silt and clay fractions. Silica, Zr and Ti exist in soils in sand size grains mainly as quartz for Si, zircon for Zr and anatase, rutile or ilmenite for Ti, all of which are highly resistant to weathering (Cornu *et al.* 1999; Stiles *et al.* 2003).

8. Distribution of Elements Between Size Fractions on Khon Buri Catena

The relative contributions of fine sand, silt and clay fractions to the amount of each element in soils on Khon Buri catena are shown in triangular graphs (Figure 40). Note that this representation does not include any contribution from coarser sand which is likely to be minor for most elements as this fraction is mostly a minor constituent and consists almost entirely of quartz. Aluminum, Si, Fe, Ti, Mg, K, Co, Cu, Zn, Cr, Ni, Rb, Sr and V are mostly associated with the clay fraction. Calcium and Zn are dominant in both the silt and clay fractions. Zirconium is abundant in the silt since resistant zircon is most abundant in the silt sized fraction (Sudom and Arnaud, 1971; Alloway, 1995). Phosphorus is dominant in the sand fraction possibly as residual apatite grains, apart from in the crest soil where much P is in the clay and

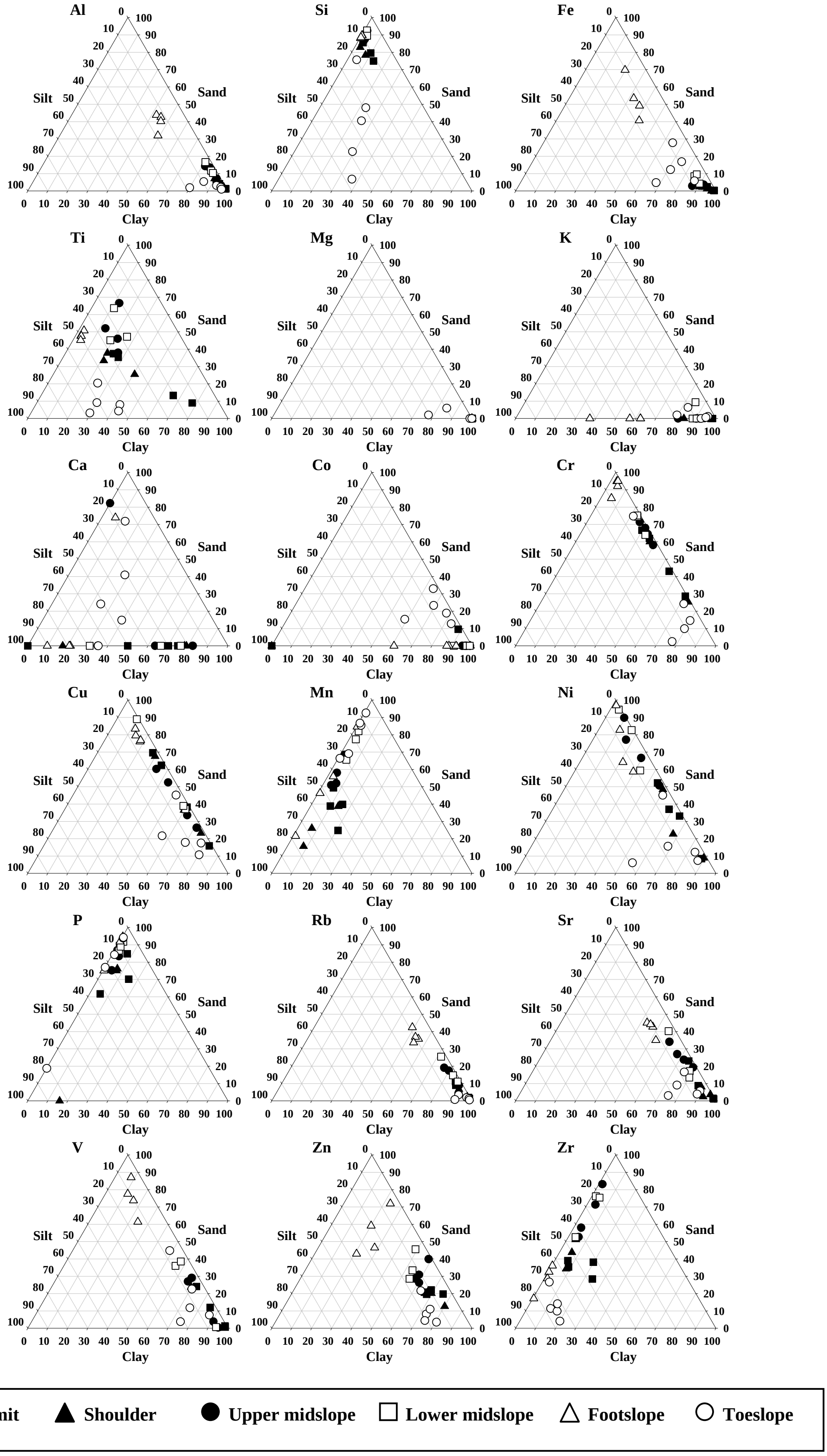


Figure 39 Triangle graphs of elements located within the sand, silt and clay fractions for Nam Phong catena.

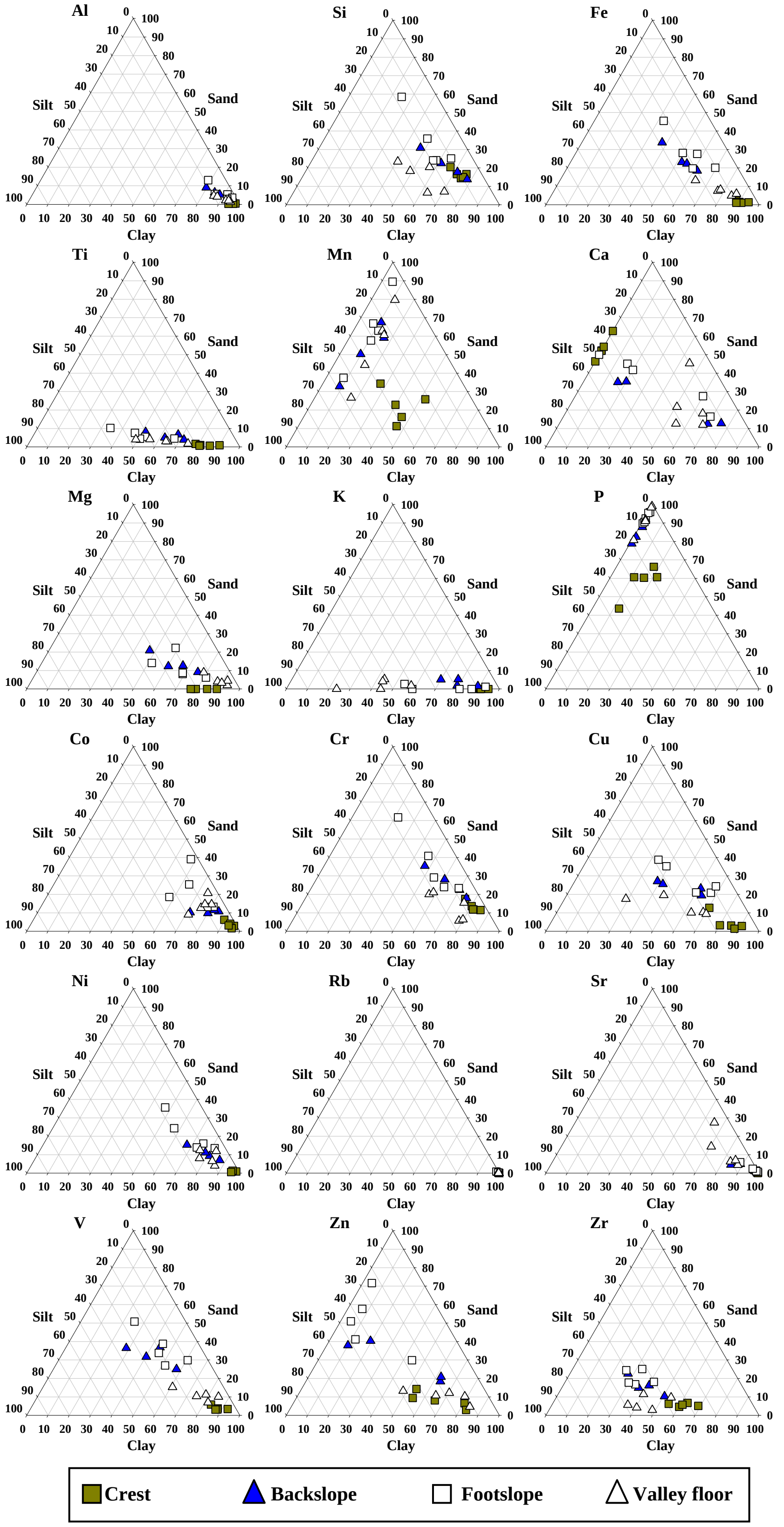


Figure 40 Triangle graphs based on the content (not concentrations) of elements located within the sand, silt and clay fractions for Khon Buri catena.

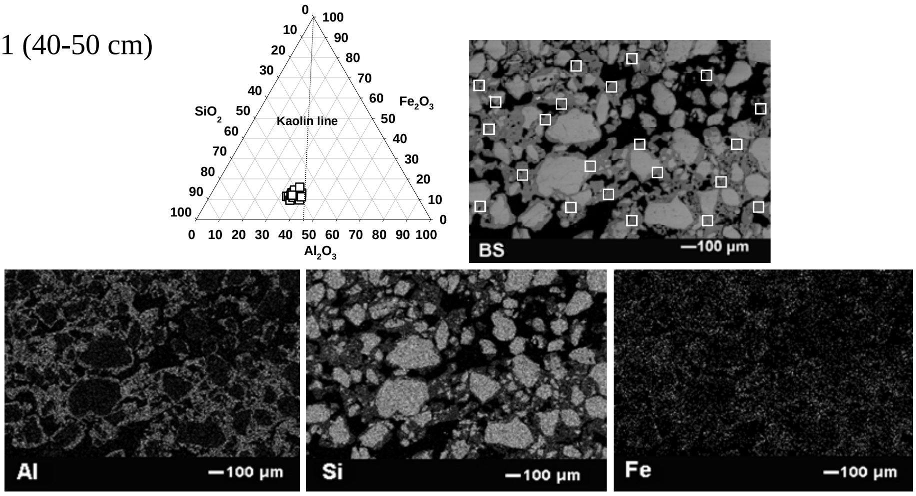
silt. Similarly much of the Mn in the crest sample is in the clay and silt but in most other samples it is in the sand and silt. In general, the distribution of minor elements between size fractions shows that most of elements are located in the clay fraction which therefore has an important role as a reservoir of heavy metals and plant nutrient elements (Song *et al.*, 1999).

9. Spatial Distribution of Major Elements in Soil Materials on Nam Phong Catena

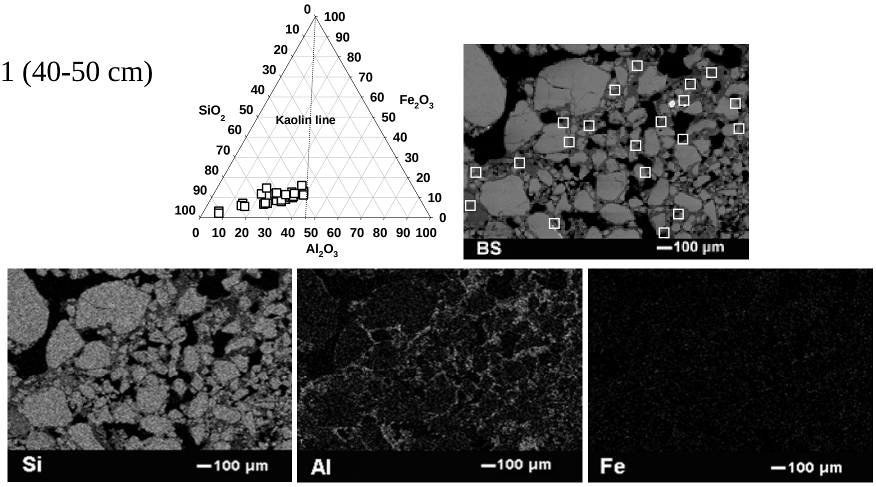
The SEM images of the thin sections of the soils on the upslope position on the catena are quite similar and show various sizes and shapes of quartz grains mixed with little matrix in a dominantly grain support matrix. The element mapping (Figures 41a, b, c, d, e) show that the major constituent in the soils in the high landscape positions are Si and minor amounts of Al and Fe which is consistent with the bulk mineralogical and chemical compositions discussed earlier. The matrix of the soil at the summit position has the most uniform chemical composition being a mixture of kaolin with iron oxide as indicated by the normalized element composition of the matrix which mostly falls on the 'kaolin line' (Figure 41a). In addition, this soil exhibits relatively little evidence of clay illuviation as is also the case for other soils. The soil matrix on the shoulder, midslope and footslope positions vary more widely in chemical composition. Data points are displaced from the 'kaolin composition line' (Figures 41b, c, d, e) towards the SiO_2 apex may indicate that some very fine grained quartz is present within the soil matrix. Displacement of the data points from the 'kaolin line' may also be attributed to the very thin coatings of soils matrix on quartz grain, so that some of the Si X-rays originated from the adjacent sand grains.

The Al, Si, Fe and Ca mapping (Figure 42) of soil from the toeslope position reveals that this soil also contains much Si, however it contains relative higher Al than other soils. Also, most of data points are located away from the 'kaolin line' toward to the SiO_2 apex. This is corresponds to the presence of illite in this soil as very little fine-grained quartz occurs in this soil. Authigenesis of illite probably occurs in the toeslope soil (Olsen *et al.*, 2000; Thompson and Ukrainczyk, 2002).

a
Bt1 (40-50 cm)



b
Bt1 (40-50 cm)



c
Bt5 (155-182 cm)

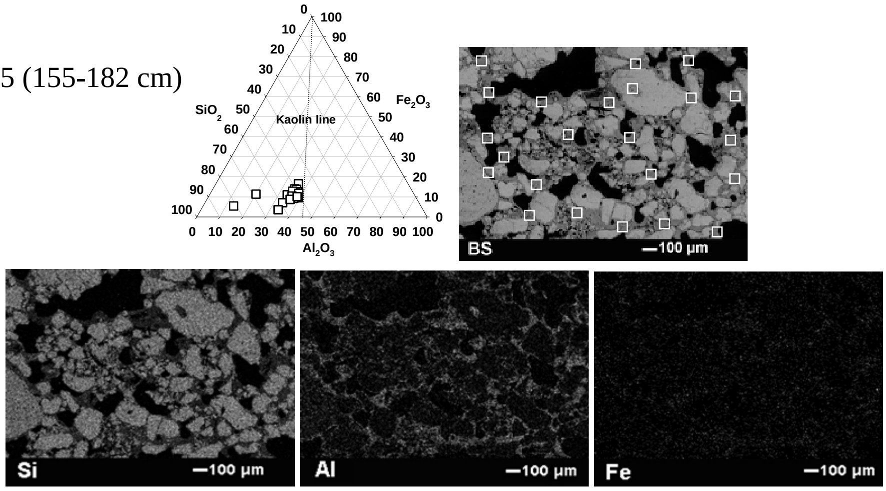
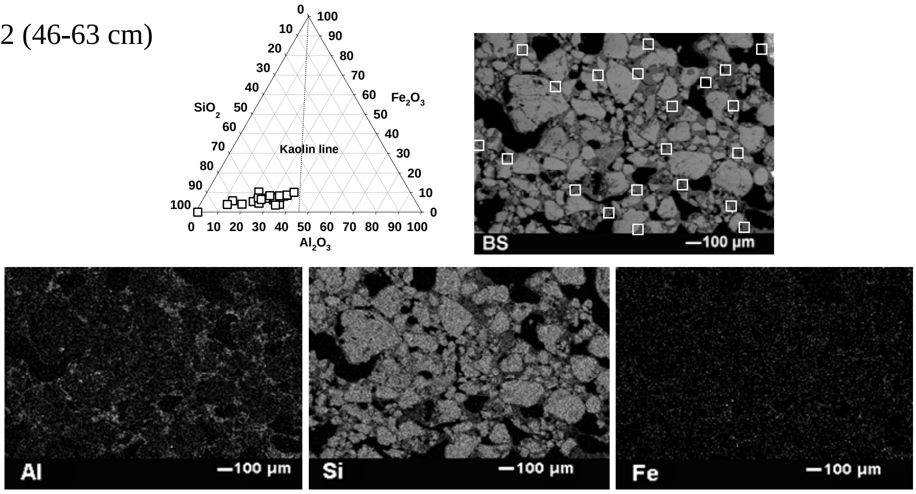


Figure 41 Backscattered electron micrographs, EDS element (Si, Al and Fe) maps and normalized composition triangular graph for the soil on the summit (a), shoulder (b), upper midslope (c), lower midslope (d), and footslope (e) of Nam Phong catena.

d
Bt2 (46-63 cm)



e
Bw (30-45 cm)

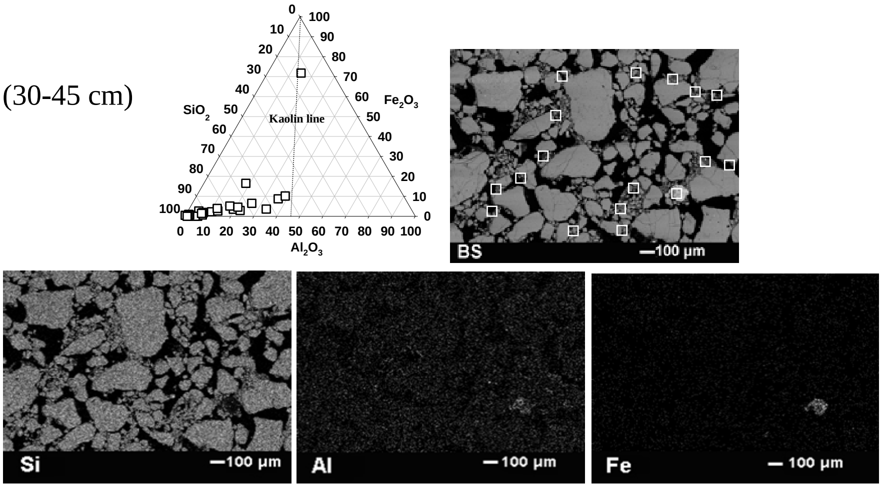


Figure 41 (Cont.)

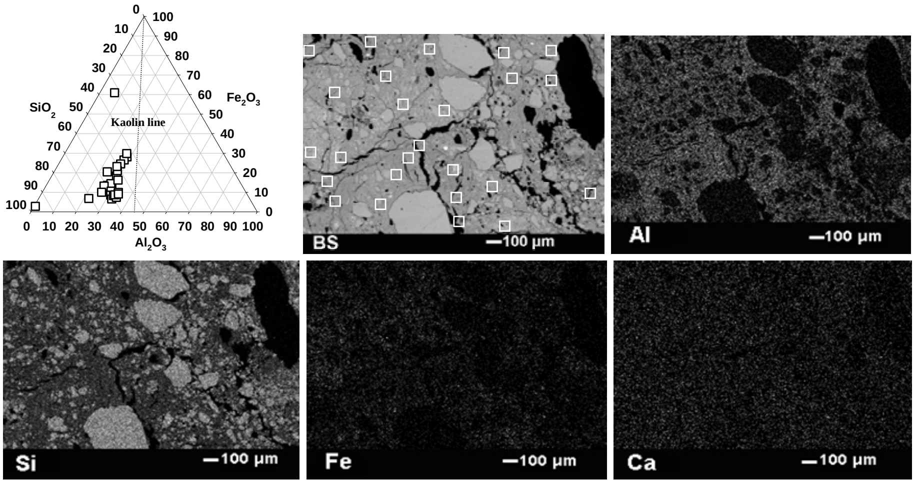


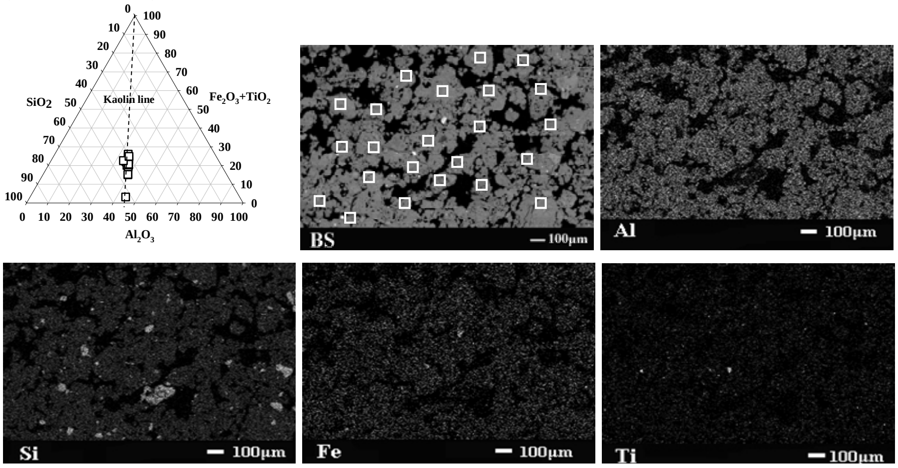
Figure 42 Backscattered electron micrographs, EDS element (Al, Si, Fe and Ca) maps and normalized composition triangular graph for the Btcg (5-23/30 cm) horizon of soil on the toeslope of Nam Phong catena.

10. Spatial Distribution of Major Elements in Soil Materials on Khon Buri Catena

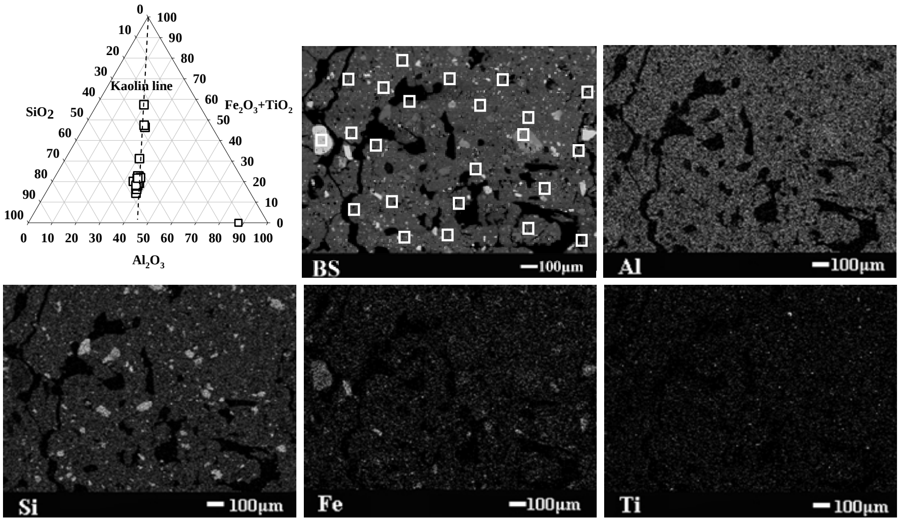
The SEM image of a thin section of crest soil show randomly distributed sand to silt sized quartz grains in a fine-grained clay-iron oxide matrix (Figure 43a). The Ti mapping also shows a presence of silt to fine sand sized grains of TiO_2 or $FeTiO_3$. The normalized element composition of the matrix falls on the kaolin composition line hence the soil matrix is simply an intimate mixture of kaolin with Fe and Ti oxides, showing little spatial variation in composition between the millimeter-sized analyzed area of matrix shown in Figure 43a.

The micromorphology of soils on the backslope and footslope positions is quite similar. There are a few oriented ferri-argillans on pore walls and microped surfaces providing evidence of illuviation. The soil matrix of backslope and footslope soils consist predominately of various mixtures of kaolin and Fe_2O_3/TiO_2 oxides as most data points fall on the ‘kaolin line’(Figures 43b and c). However there is a much wider range of compositions than for the crest soil and analyses for the footslope soil are mostly slightly displaced from the ‘kaolin line’ towards the SiO_2 apex indicating that very fine-grained quartz is present in the matrix. XRD did not indicate the presence of a Si-rich clay mineral in this profile. Another possible cause of displacement of data points away from the kaolin line towards lower Al_2O_3 values is that the kaolin in many tropical soils contains Fe substituting for Al (Murali *et al.*, 1978; Hart *et al.*, 2002b) and kaolin in these soils contains much structural Fe. Quartz sand grains are distributed through the soil matrix along with occasional Ti rich grains of either ilmenite or rutile (Figures 43b and c). The darker red color of some parts of the soil matrix corresponds to a higher Fe concentration (Bowell, 1993) as indicated by high (Fe_2O_3+TiO_2) concentration for some points in Figures 43b and c. The footslope soil contains more Fe_2O_3-rich nodules than soils on backslope positions as is evident from the Fe-image in Figure 43c. The greater abundance of nodules in soil on the footslope may reflect lateral transportation from upslope sites of Fe and Mn which are immobilized in the footslope soil in the form of Fe, Mn rich nodules (Yaalon *et al.*, 1971). Typical X-ray spectra of nodules are shown in Figure 44 indicating that

a: Bo1 (130-160 cm)



b: Bt1 (35-59 cm)



c: Btc4 (103-130 cm)

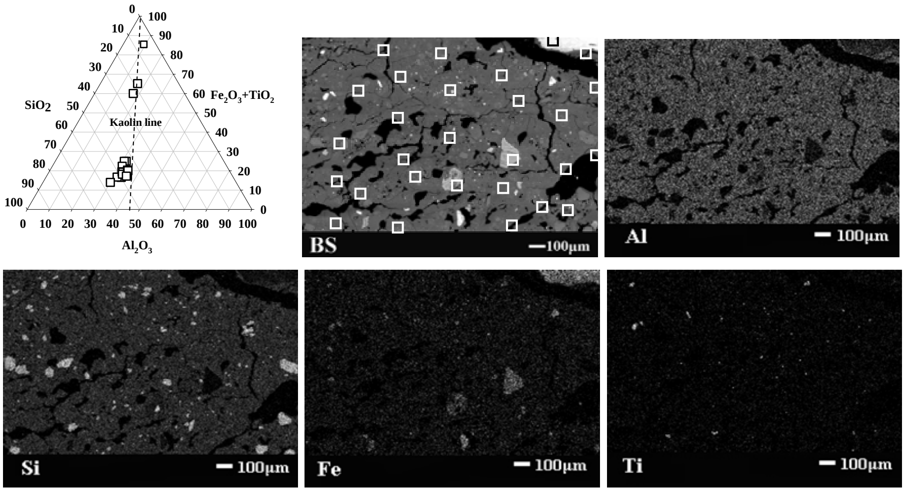


Figure 43 Backscattered electron micrographs, EDS element (Si, Al, Fe and Ti) maps and normalized composition triangular graph of soils on the crest (a), backslope (b) and footslope (c) of Khon Buri catena.

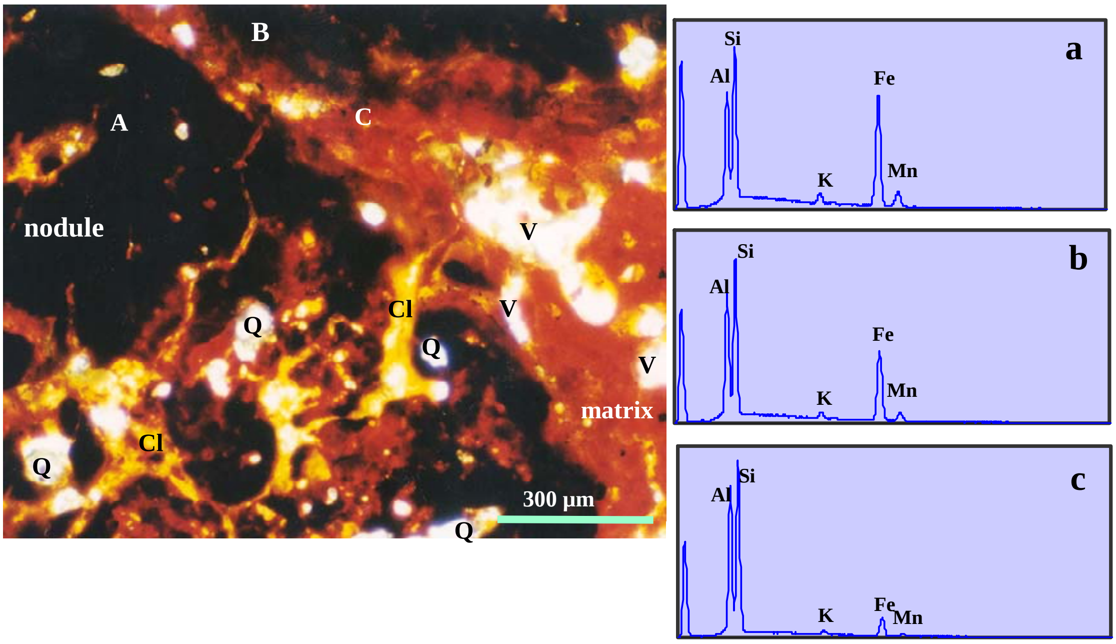


Figure 44 Photograph of a typical nodule from Btc4-horizon (103-130 cm) of soil on the footslope position: EDS spectra of point within nodules (a, b) and matrix (c). These compositions are consistent with nodules being simple iron and manganese oxide indurated regions of the kaolin-quartz matrix (Q = quartz, V = void, Cl = clay coated).

the nodules consist mostly of kaolin (Al, Si) with abundant Fe and some Mn. The presence of K in nodules may indicate that the Mn mineral is crytomelane (KMn_8O_{16}).

The element mapping (Figure 45) of the thin section of valley floor soil shows data points that are located off the kaolin line towards the SiO_2 apex. This is a consequence of the presence of smectite (dioctahedral) as a major constituent of the matrix. The smectite contains a higher concentration of SiO_2 than does kaolin and theoctahedral cation site of smectite is occupied by Mg and Fe in addition to Al thus further reducing the Al_2O_3 concentration (Borchardt, 1977; Birkeland, 1999). Very small quartz grains are abundant in all four soils and although quartz is not a primary mineral in basalt, Beckmann *et al.* (1974) proposed that it could be a product of weathering or geological alteration.

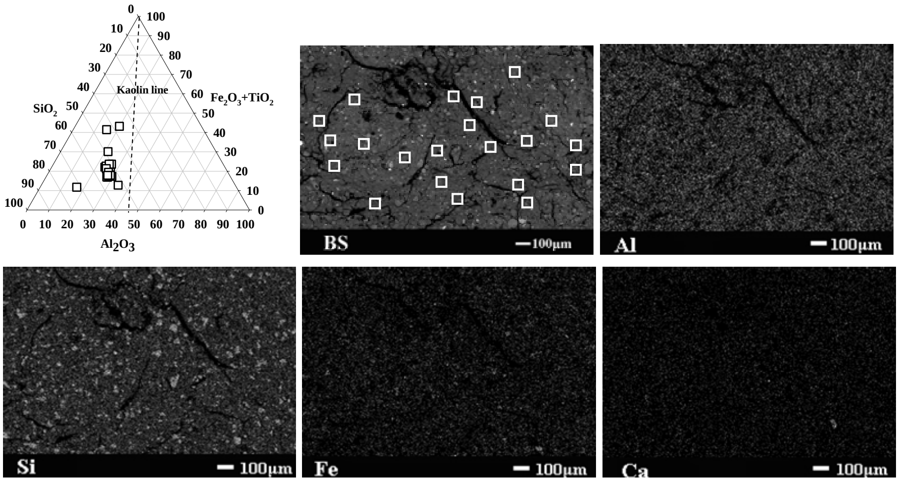


Figure 45 Backscattered electron micrographs, EDS element (Si, Al, Fe and Ti) maps and normalized composition triangular graph for the Bg2 (50-76 cm) horizon of soil on the valley floor of Khon Buri catena.

11. Summary

Soils at all positions on Nam Phong catena are dominated by quartz and containing much Si, together with minor Al and Fe. The major elements are closely related to minerals present in soils as kaolin is major clay mineral occurring along with smaller amounts of iron oxide in the clay fraction in soils at all positions. Illite and vermiculite are present in the footslope and toeslope positions. Only quartz was detected by XRD in the silt and fine sand fractions so less than about 1 percent of other minerals is present. Factor analysis does not supported the hypothesis that there would be systematic differences in element composition in the whole soil, fine sand and silt samples between the several soils on the catena. The element compositions of upslope soil show little variation and the chemical compositions of upslope profiles overlap closely. However, the chemical composition of the toeslope soil is distinctly different from the soils on higher positions as indicated by Al group (Al, Co, Ca, Mg, K, Sr, Cs, Rb, Ga, Zn, Ni, Li, Mn, Ti) and there is a wide variation in chemical component of horizons of the toeslope soil. For the clay fraction, the different concentrations of Si group (Si, Ni, Mn, Co, Mg, K, Ba, Pb) and Ca group (Ca, Zn, Cu, Sr, Cr, P) elements result in the soils on toeslope and footslope being distinctly different from other soils. The factor based on the Al group (Al, Fe, Zr, Ti, V) causes the soils on summit, shoulder and midslope to overlap to some extent but these soils are different from other soils and show moderate variation with depth. The small variations in the chemical composition of upslope soils are probably due to different degrees of weathering of the same parent rock, whereas soil on the toeslope position has a quite different elemental composition which is possibly due to both a difference in composition of the parent rock and formation of authigenic minerals.

The chemical compositions of all the soils on Khon Buri catena are in the range of basalt derived soils elsewhere in the world as reported by Alloway (1995). The crest soil is the most weathered, having uniform Al, Si, Fe and Ti concentrations and very low amounts of Ca, Mg and K throughout the profile. Kaolin and iron oxide minerals are major constituents with little quartz and no weatherable minerals present in this soil. Backslope and footslope soils are also highly weathered soils and have similar Al, Si, Fe and Ti distribution patterns to those in soil on the crest, but they contain higher amount of Mn in the Fe and Mn nodules. The valley floor soil is less severely weathered as it is on the lowest position of the landscape where there is a high water table and leached ions accumulate resulting in the authigenesis of smectite. The high amounts of Mg, Ca and K have been derived from weathering of basalt upslope. This geochemical environment has enabled feldspar to be preserved in the silt and fine sand fractions of the valley floor soil.

Factor analysis allowed the chemical analyses of soil samples to be compared both within and between profiles. On the basis of the element composition of the whole soil, fine sand, silt and clay fractions, crest soil is most uniform, backslope soil is quite uniform, footslope soil is quite diverse and overlaps with backslope soil except for the silt and clay, and the valley floor soil is most highly diverse. This pattern is probably due to the difference in chemical weathering intensity along the landscape. Three main elemental affinity groups are recognized for whole soils; the Al group (Al, Ti, Li, Cs, Zr, Mo) and the Ca group (Ca, Si, K, Mg) demonstrate that; soil on crest and valley floor are distinctly different. The Fe group (Fe, Mn, P, Ga, Cr, Pb, Rb, V, Cu, Zn, Ni, Co, K, As) results indicate that backslope and footslope compositions overlap however they differ for the other two soils. For the fine sand, the soils on crest and valley floor are distinctly different as based on the different abundance of Zr, Cr and Si, Ca, Sr respectively. The different abundances of the Mn group (Mn, Mg, Pb, Co, Pb, K) and Fe group (Fe, Rb, Ni, P, U, Zn, Ga, V, Al, Cu, As, Ti, Cs, Li, Mo) cause the soils on the backslope and footslope to be quite different from the other two soils, however these slope soils overlap in composition. The chemical compositions of both silt and clay fractions are discrete for all four profiles. For silt, the different abundances of Ti group (Ti, Al, Li, Zr, Cs), Fe group (Fe, Mn, P, Co, U, As, Ni, Cu, Cr, Mg, V, Zn, Mo, Rb, Ga, Cd) and Ca group (Si, Ca, Sr, K, Pb) clearly separate the soils on crest, backslope and footslope, and valley floor positions. The abundance of Mg group (Mg, Ca, Si, Mn, Sr, Cr) in clay in the valley floor soil results in a distinctly different chemical composition from clay in the other soils.

It is concluded that different extents and types of weathering have occurred in this catena. Alteration of the parent basalt under a tropical climate has produced kaolin and iron oxide minerals as the dominant soil materials for well drained slope sites. The geochemistry of the soils mostly reflects this process. In the valley floor soil, the accumulation of leached ions has resulted in the crystallization of smectite and carbonate with their associated element suite. This catenary sequence of materials and processes represent a clear example of landscape scale chemical evolution of soils described by Millot (1970).

Micromorphological Characteristic of Soils on Nam Phong and Khon Buri Catenae

Micromorphological characteristics of soils on Nam Phong and Khon Buri were analyzed using soil thin section under the polarized light microscope based on standard micromorphological techniques as described by Bullock *et al.* (1985). This section characterizes the micromorphological features relate to development of the soils and other physico-chemical properties.

1. Description of the Main Micromorphological Features

The summarized micromorphological features of the soils on Nam Phong and Khon Buri catenae are given in Table 9. The dominant micromorphology of soils on Nam Phong and Khon Buri catenae are shown in Figures 46 and 47 respectively.

1.1 Microstructure

In the soils of Nam Phong catena, pellicular grain structure and bridged grain structures are the main microstructures of the soils on the upslope positions indicating that these soils are highly developed (Goenadi and Tan, 1989). Single grain structure is well expressed in soils on the midslope and footslope positions. The toeslope soil is dominated by bridged grain structures and subangular blocky structure along with local intergrain microaggregates. For Khon Buri catena, soil on the crest position has granular mixed with subangular blocky structures and locally a crumb structure, which is interpreted to result from long term biological activity (Nunes *et al.*, 2000; Schaefer, 2001). Subangular blocky structure is mainly microstructure for the soils on the backslope and footslope positions. Granular structure is also present in the surface soil on the footslope position. The subangular blocky structure and locally a crack structure are well expressed in the valley floor soil.

1.2 Voids and Porosity

The main voids are simple packing voids along with few vughs, chambers and vesicles present in the upslope soils on Nam Phong catena. Planar voids are the major voids along with chambers, vughs and channel voids in soil on the lowest position of both catenae. For Khon Buri catena, the compound packing void is the main void in upslope soils. Both smooth and rough edges voids occur. Planar voids are usually intra-aggregated and consisted of straight and zig-zag types.

Table 9 Micromorphological features of soils on Nam Phong and Khon Buri catenae

Horizon (depth0	Microstructure	c:f at 10 µm	c/f related distribution	b-fabric	Pedofeature
	Nam Phong catena				
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic				
Ap (0-20cm)	Pellicular grain, bridged grain	95:5	Chitonic	Undifferentiated	Typic nodules, excrements of animal
E (20-40 cm)	Pellicular grain, bridged grain	90:10	Chitonic	Undifferentiated, grano-porostriated	Clay-iron oxide coating
Bt2 (59-73 cm)	Pellicular grain, bridged grain	85:15	Chitonic	Undifferentiated, grano-porostriated	Clay-iron oxide coating, microlaminated coating
Bt4 (105-142 cm)	Bridged grain, pellicular grain	80:20	Gefuric	Undifferentiated, grano-porostriated	Clay-iron oxide coating, microlaminated coating
Bt6 (172-205+ cm)	Bridged grain, pellicular grain	70:30	Gefuric	Undifferentiated, grano-porostriated	Clay-iron oxide coating, microlaminated coating
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic				
Ap (0-23 cm)	Compact grain	90:10	Chitonic	Undifferentiated	Iron impregnative nodules
E (23-35 cm)	Compact grain	92:8	Chitonic	Undifferentiated	Iron impregnative nodules
Bt1 (35-58 cm)	Pellicular grain, bridged grain	85:15	Gefuric	Undifferentiated, grano-porostriated	Clay-iron oxide coating
Bt2 (58-82 cm)	Bridged grain	80:20	Gefuric	Undifferentiated, grano-porostriated	Clay-iron oxide coating, microlaminated coating
Bt3 (82-110)	Bridged grain	80:20	Gefuric	Undifferentiated, grano-porostriated	Clay-iron oxide coating, microlaminated coating, iron impregnative nodules
2C (140-190+ cm)	Subangular blocky	85:15	Closed prophyric	Undifferentiated, grano-porostriated	Clay-iron oxide coating, microlaminated coating
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic				
Ap (0-20/30 cm)	Single grain	98:2	Monic	Undifferentiated	-
E (30-45)	Single grain	98:2	Monic	Undifferentiated	-
Bt1 (45-67 cm)	Bridged grain, single grain	92:8	Gefuric, monic	Undifferentiated	Clay bridging
Bt3 (100-130 cm)	Bridged grain, single grain	90:10	Gefuric	Undifferentiated	Clay-iron oxide coating
Bt5 (155-182 cm)	Bridged grain	85:15	Gefuric	Undifferentiated	Clay-iron oxide coating, silty clay capping, psedomorphic nodules
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic				
Ap (0-27/35 cm)	Single grain, bridged grain	93:7	Monic, gefuric	Undifferentiated, stipple speckled	-
Bt2 (46-63 cm)	Bridged grain	90:10	Gefuric	Undifferentiated	Clay-iron oxide coating, iron oxide impregnative material
2BC (80-100 cm)	Bridged grain	90:10	Gefuric	Undifferentiated	Clay-iron oxide coating, iron oxide impregnative material, psedomorph after rock fragments
2C2 (130-180+ cm)	Bridged grain	90:10	Gefuric	Undifferentiated, poro-granostriated	Clay-iron oxide coating, microlaminated coating

Table 9 (Continued)

Horizon (depth0	Microstructure	c:f at 10 µm	c/f related distribution	b-fabric	Pedofeature
	Footslope: Oxyaquic Haplusalf, sandy, siliceous, isohyperthermic				
Ap1 (0-10/20 cm)	Single grain, bridged grain and intergrain microaggregate	95:5	Monic, gefuric, enaulic	Undifferentiated	-
Ap2 (20-30 cm)	Single grain, bridged grain and intergrain microaggregate	95:5	Monic, gefuric	Undifferentiated	-
Bw (30-45 cm)	Single grain, bridged grain and intergrain microaggregate	95:5	Monic, gefuric	Undifferentiated	-
Bt (45-80 cm)	Single grain, bridged grain and intergrain microaggregate	95:5	Monic, gefuric	Undifferentiated	-
Btg1 (80-110 cm)	Compact grain	95:5	Monic, gefuric	Undifferentiated	Clay coating
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic				
Apg (0-5 cm)	Bridged grain, intergrain microaggregate	75:25	Gefuric, enaulic	Stipple speckled	Typic nodules, iron oxide impregnative nodules
Btcg (5-23/30 cm)	Subangular blocky	70:30	Closed prophyric	Stipple speckled, poro-granostriated	Clay coating, iron oxide impregnative nodules, aggregate nodules
Btg1 (23-48 cm)	Subangular blocky	60:40	Closed prophyric	Stipple speckled, poro-granostriated	Clay coating, iron oxide impregnative nodules, aggregate nodules, carbonate impregnative material
Btg2 (48-80 cm)	Subangular blocky	20:80	Closed prophyric	Stipple speckled, poro-granostriated	Clay coating, iron oxide impregnative nodules, aggregate nodules, carbonate impregnative material
Btg4 (113-143 cm)	Subangular blocky	5:95	Closed prophyric	Stipple speckled, poro-granostriated	Aggregate mottle, carbonate impregnative material, slickenside
BCg1 (143-162 cm)	Subangular blocky	5:95	Closed prophyric	Stipple speckled, poro-granostriated	Aggregate mottle, carbonate impregnative material, clay coating, microlaminated coating

A backscatter micrograph of the upslope soils on Nam Phong catena (Figure 48) shows mostly of the pore and void in the soils resulting from the arrangement of sand grains. A loose arrangement of sand and silt particles with interparticle voids in various diameters are evident in surface soils but the packing of the silt particles among sand particles are found in the subsurface horizon. For the soils on Khon Buri catena (Figure 48), voids and pores are between the soil aggregates with various sizes.

Table 9 (Continued)

Horizon (depth0	Microstructure	c:f at 10 µm	c/f related distribution	b-fabric	Pedofeature
Khon Buri catena					
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic				
Ap2 (15-30 cm)	Granular, subangular blocky, crumb	15:85	Open prophyric	Undifferentiated, poro-granostriated	Microlaminated coating, clay infilling
Bto1 (30-51 cm)	Granular, crumb, subangular blocky	8:92	Open prophyric	Undifferentiated, poro-granostriated	Typic nodules
Bto3 (70-100 cm)	Granular, crumb, subangular blocky	5:95	open prophyric	Undifferentiated, circular, poro-granostriated	Clay-iron coating, clay infilling, impregnative nodules
Bo1 (130-160 cm)	Crumb, granular, subangular blocky	2:98	Open prophyric	Undifferentiated, circular, poro-granostriated	Clay-iron coating, clay infilling, impregnative nodules
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic				
Ap2 (11-28/30 cm)	Subangular blocky, granular	15:85	Open prophyric	Undifferentiated, poro-granostriated	Clay fragment, typic nodules
Bt1 (30-54 cm)	Subangular blocky	12:88	Open prophyric	Undifferentiated, poro-granostriated	Clay fragment, typic nodules
Bt2 (59-88 cm)	Subangular blocky	8:92	Open prophyric	Undifferentiated, poro-granostriated	Clay fragment, typic nodules, psedomorphic nodules
BCr1 (119-151 cm)	Subangular blocky	10:90	Open prophyric	Undifferentiated, poro-granostriated	Clay fragment, typic nodules, psedomorphic nodules
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic				
Ap2 (12-30 cm)	Granular	20:80	Open prophyric	Undifferentiated	Typic nodules, psedomorphic nodules
Btc2 (52-72 cm)	Subangular blocky, granular	25:75	Open prophyric	Undifferentiated	Typic nodules, psedomorphic nodules, clay fragment
Btc4 (103-130 cm)	Subangular blocky, granular	25:75	Open prophyric	Undifferentiated	Typic nodules, psedomorphic nodules, clay fragment
BCrt (150-180 cm)	Granular, subangular blocky	25:75	Open prophyric	Undifferentiated	Typic nodules, psedomorphic nodules, clay fragment
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic				
Apg (0-15 cm)	Subangular blocky, crack	10:90	Open prophyric	Stripple speckled, iron stain	Clay coating, aggregate iron mottle, typic nodule
Bssg (25-50 cm)	Crack, subangular blocky	10:90	Open prophyric	Stripple speckled, mosaic speckled, poro-granostriated	Clay fragment, aggregate iron mottle, typic nodule
Bg2 (76-100/110 cm)	Crack, subangular blocky	8:92	Open prophyric	Stripple speckled, mosaic speckled, poro-granostriated	Clay fragment, aggregate iron mottle, typic nodule
BC1 (110-133 cm)	Subangular blocky, crack	15:85	Open prophyric	Stripple speckled, mosaic speckled, poro-granostriated	Clay fragment, aggregate iron mottle, typic nodule, carbonate impregnative material
Crg (160-180+ cm)	Subangular blocky, crack	20:80	Open prophyric	Stripple speckled, mosaic speckled, poro-granostriated	Clay fragment, aggregate iron mottle, typic nodule, carbonate impregnative material

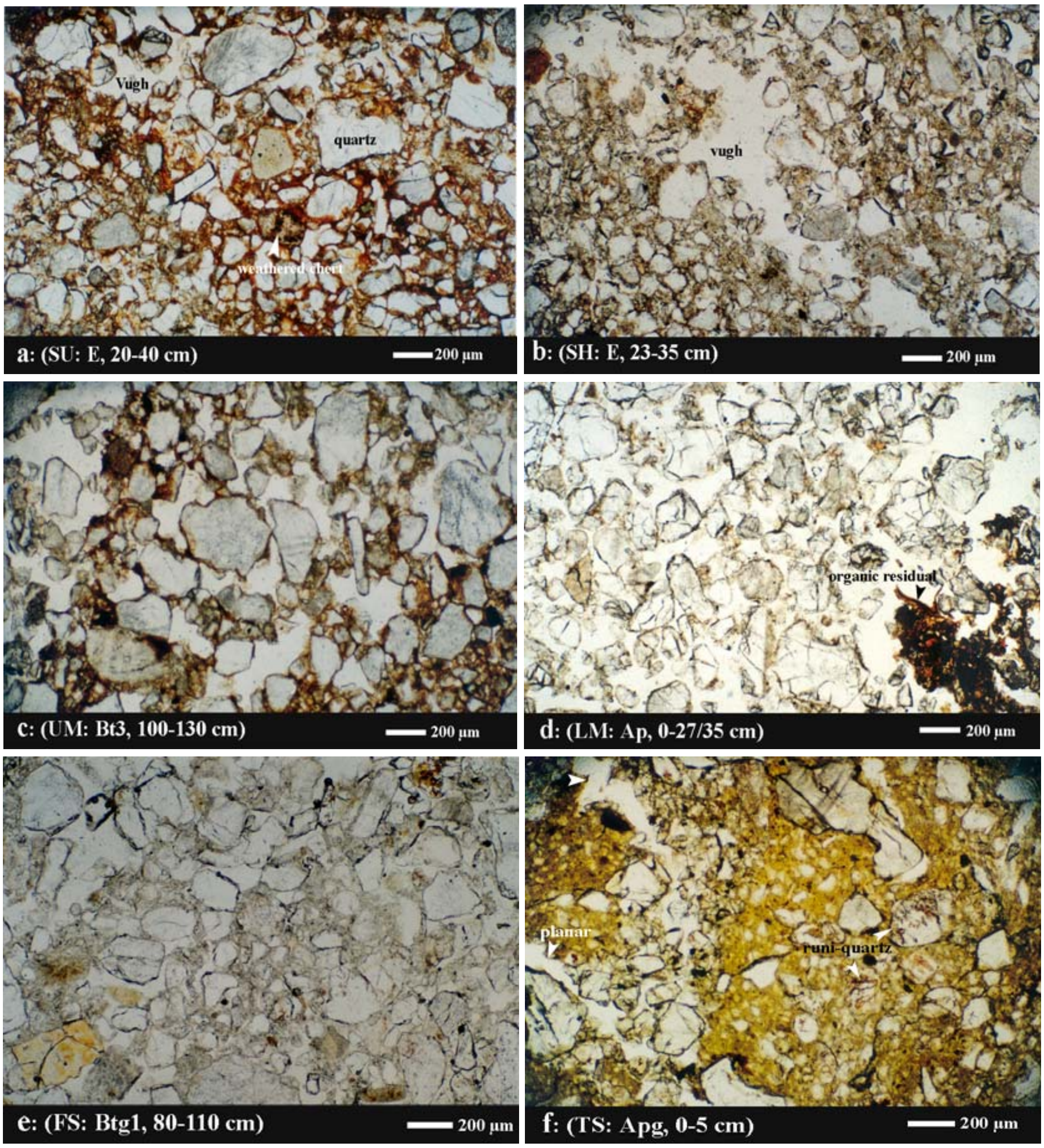


Figure 46 Thin section micrographs of soils on Nam Phong catena under plane polarized light, showing runi-quartz, subangular to rounded quartz with various size which most of quartz grains are broken, poorly sorted to moderately sorted. The dominant micromorphological features are:
(a, c) bridged grain structure with gefuric of soils on summit and midslope
(b) compact grain with chitonic of soil on shoulder
(d, e) single grain with monic of soils on footslope and midslope
(f) subangular blocky structure with closed prophyric of soil on the toeslope.

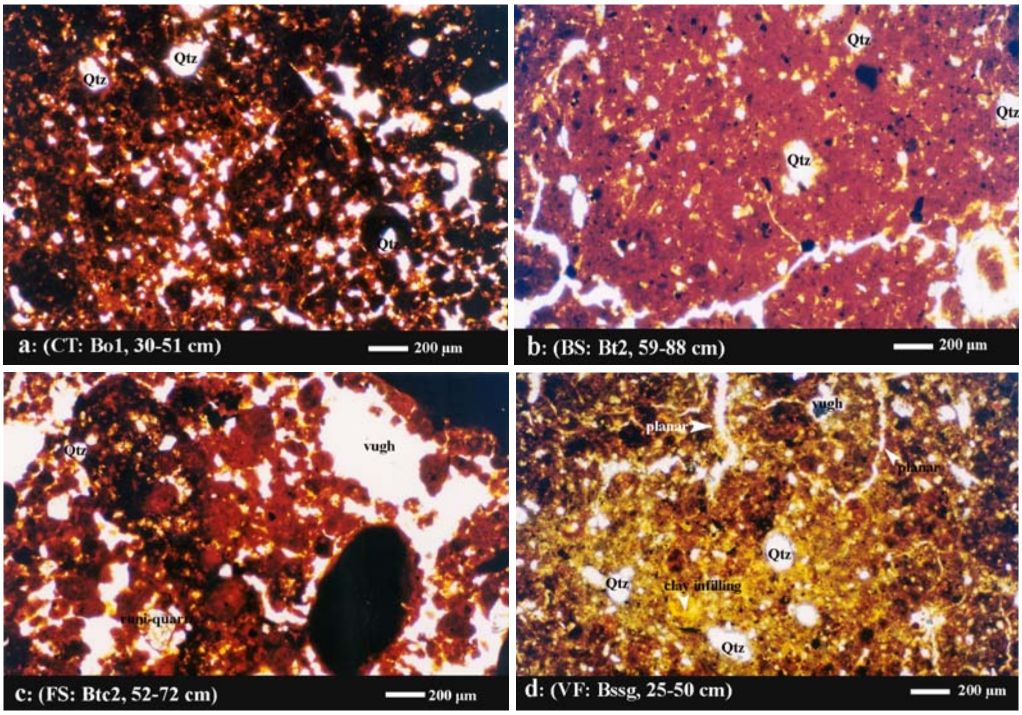


Figure 47 Thin section micrographs of soils on Khon Buri catena under plane polarized light, showing sub rounded-rounded quartz. Thy are moderately sorted to well sorted. The c/f ratio are open prophyric. The dominant micromorphological features are:
(a) crumb and granular structure for the soil on crest
(b) subangular blocky structure for the soil on backslope
(c) granular structure for the soil on footslope
(d) crack structure for the soil on valley floor

1.3 The b-fabric and Groundmass

For soils on Nam Phong catena, the c/f related distribution are mainly chitonic in surface of upslope soils. The presence of gefuric is obvious in the deep horizon of the soils on the summit and shoulder positions and only a little observed in deep horizon of the soils on the midslope and footslope positions. The gefuric is mainly c/f related distribution of the toeslope soil with local enaulic occurring in surface soil; also the closed prophyric are found in the subsurface horizon. The c/f related distribution of all soils on Khon Buri catena are open porphyric due to a presence of a continuous fine matrix.

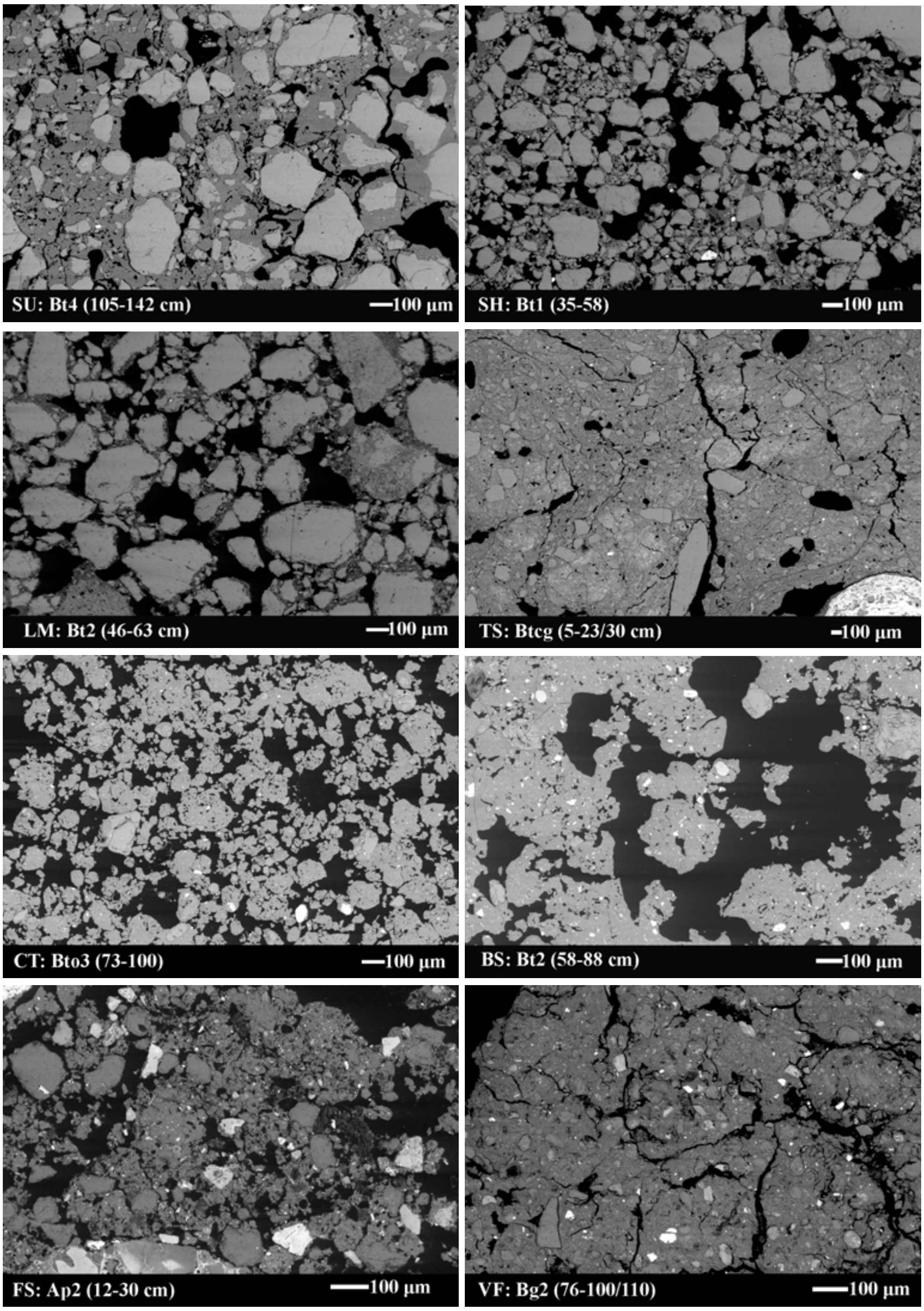


Figure 48 Backscatter electron micrographs of thin sections; the voids are black, homogeneous gray areas are quartz grains, very light particles are much heavier mineral than quartz and the heterogeneous gray area are fine silt and clay particles and associated porosity. The selected horizons represent soils on summit (SU), shoulder (SH), lower midslope (LM) and toeslope (TS) positions on Nam Phong catena; soils on crest (CT), backslope (BS), footslope (FS) and valley floor (VF) positions on Khon Buri catena.

The undifferentiated b-fabric of upslope soils (Figure 49) on both catenae is possibly due to the enrichment of Fe resulting in a brownish to dark red color which was intense enough to cause opacity. Grano- to porostriated b- fabrics are also clearly expressed in the deep horizons of upslope soils. Circular striaes occur only in deep horizon of the soil on the crest on Khon Buri catena. The humified organic fine materials scattered in groundmass are apparent in surface soil and they decrease with depth. The stipple speckling is mainly b-fabric along with few grano- to porostriated b- fabric of the soils on the lowest positions of the catenae. The speckled b-fabric is generally found in flooded soils with high clay content indicating weak plasma separation, a result of restricted swelling clay (Kalbande *et al.*, 1992). Only crystallitic b-fabric is present in the deep horizon of the soil on toeslope of Nam Phong catena. The lack of grano- and porostriated b-fabric in the surface of the valley floor soil on Khon Buri catena agrees with results of many researchers (Blokhuis *et al.*, 1990; Hussein and Adey, 1998) who reported that surface-related plasma separations (porostriation and granostriation) are rare or lacking in surface horizon of vertisols but generally increasing with depth due to a greater stresses and shearing in subsurface soil.

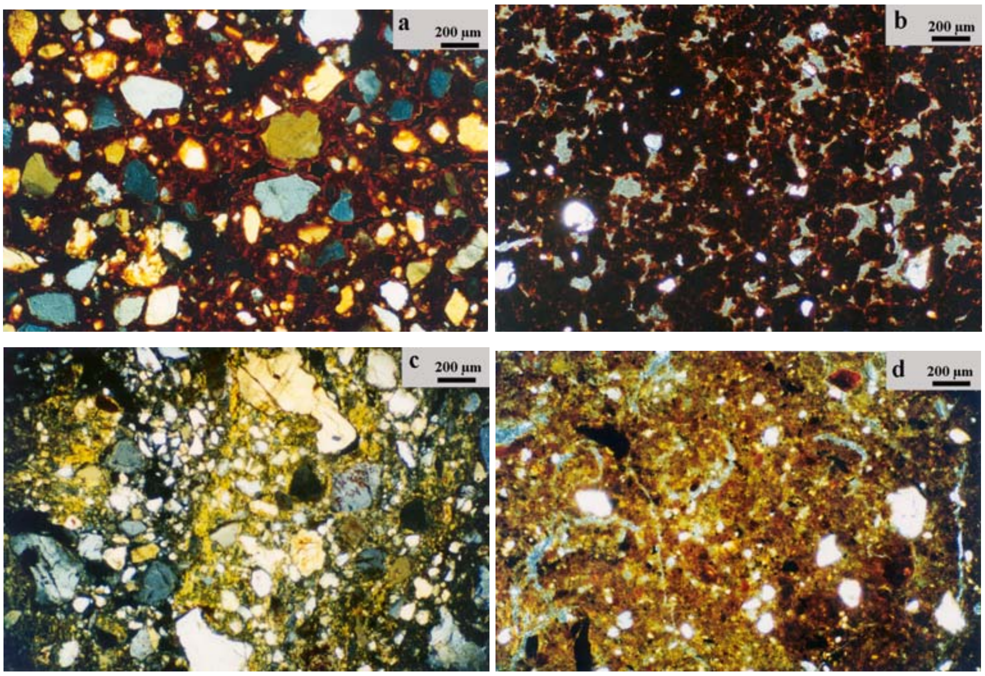


Figure 49 Thin section micrograph under cross polarized light showing dominant b-fabric of soils on both catena: undifferentiated b-fabric are dominant for upslope soils (a, b) and stripple (c) and mosaic (d) speckled b-fabric of soil on the low position on the landscape. Poro- and granostraited also predominant.

1.4 Coarse Material Component in Soils

Soils on all positions of Nam Phong catena contain quartz grains, runi-quartz, polycrystalline quartz and chert, few sandstone rock fragment and chacedony, and rare anhedral zircon and tourmaline. Chert is common in sandstone derived soils in Northeast Thailand (Tapakul Na Ayutthaya, 1994). Soils on Khon Buri catena contain mainly quartz grains, common runi-quartz and rare zircon and weathered pyroxene. The presence of runi quartz points to a material derived, at least partially, from the destruction of an older surface (Eswaran *et al.*, 1975). The presence of resistant Ti minerals and magnetite in upslope soils on Khon Buri catena indicates the influence of mafic parent material (Schaefer *et al.*, 2002). Quartz is a ubiguitous constituent of these soils, due to quartz being a highly resistant mineral in soils (Sudom and Arnaud, 1971; Cornu *et al.*, 1999; Stiles *et al.*, 2003). Soils on the backslope and footslope positions of Khon Buri catena contain weathered pyroxene and highly weathered basalt rock fragments (lithorelicts) that increase in abundance with depth indicating that the soil on the crest position is more highly weathered than soils on backslope and footslope positions.

2. <u>Nature of the Soil Plasma of the Catenae</u>

2.1 Clay Illuviation

Figure 50 shows various coatings on pore wall, ped faces and quartz grains in soils on the catenae. The presence of illuvial ferri-argillans is considered to be the evidence of clay translocation within the soil profile. In the soils on the Nam Phong catena, the micro-laminanted clay coating is clearly observed in the deep horizons of soils on summit and shoulder positions. The thin to thick ferri-argillan coatings along with gray silty clay cappings on grains occur in soils on the midslope and footslope positions. These indicate translocation and accumulation of fine materials within the soil profiles. The soils on backslope and footslope positions on Khon Buri catena have ferri-agrillan coatings on pore walls and ped surfaces. However there are only few of this coating in the crest soil. Clay fragments and clay

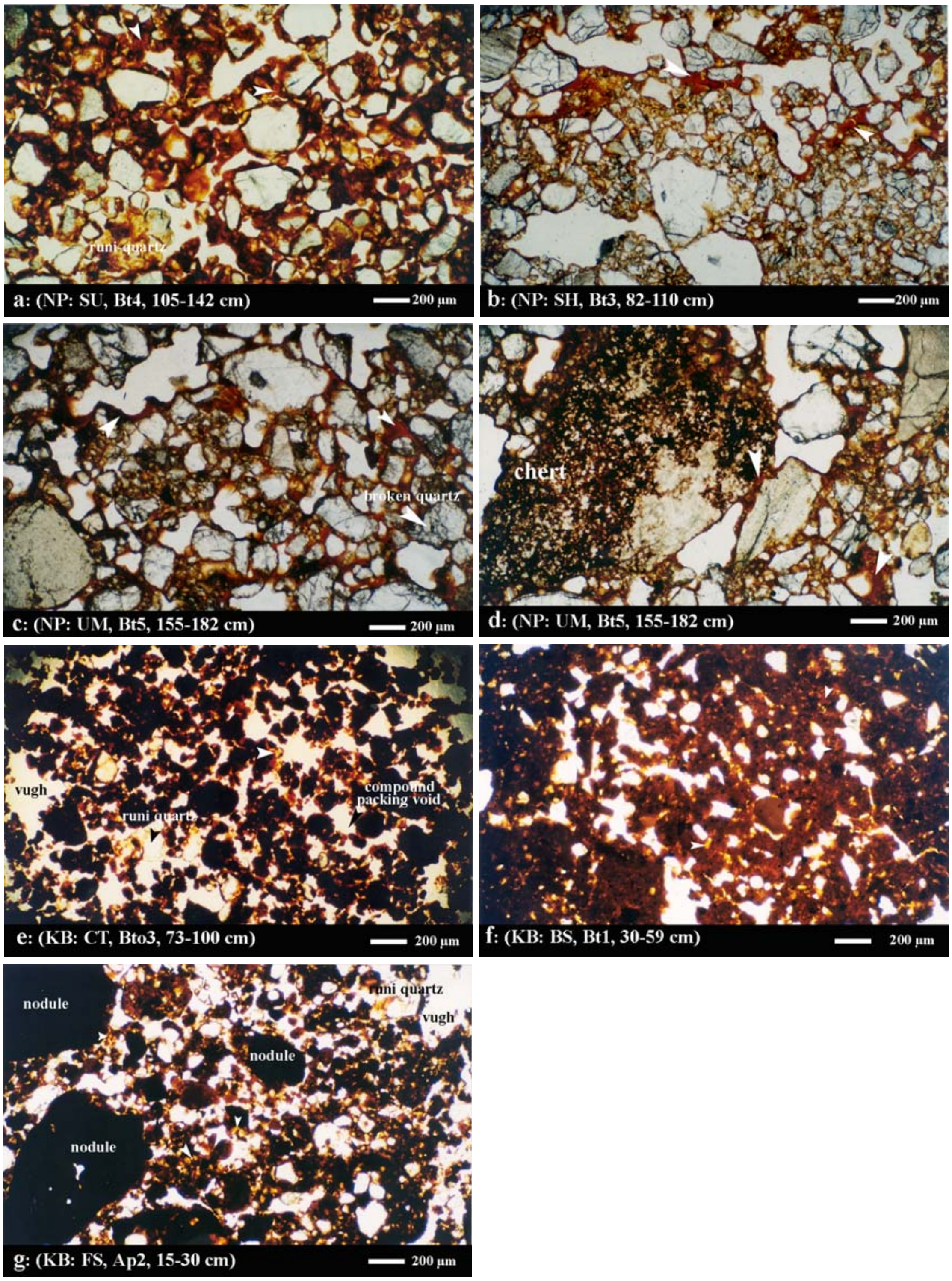


Figure 50 Thin section micrographs of soils under plane polarized light showing; red – orange laminated ferri-agrillan coatings (a, b, c, d) and yellow clay infillings (e, f, g) on some ped faces or walls of void, humified organic fine materials scattering in groundmass, iron filling in the quartz vein (runi-quartz) and chert (weathered chert).

infillings in soils on the backslope, footslope and valley floor positions possibly represent transported clay material from the upslope. The argillan and ferri-argillan on skeleton grains and pore walls indicate prolonged leaching and the oxidizing state of the solum (Kheoruenromne, 1987) of the soil on the high position of the landscape.

2.2 Fabric Characteristics and Development

As all soil formation processes affect the plasma both directly or indirectly a study of the plasma could indicate the development of the soil as a whole. Soil plasma of the upslope soils on both catenae have dark reddish brown, brown, reddish yellow reddish brown, dark red colors whereas yellowish brown and gray colors occur in the plasma of soils on the lowest part of the catenae. Generally the difference in the plasma color is attributed to a difference in the Fe content of soils in tropical region (Bennema *et al.*, 1970). The red shade of color of the fine material indicates that these soils are well-drained and that oxidizing condition prevails. For the upslope soils on both catenae, soil plasma shows undifferentiated b-fabric which possibly be associated with iron minerals. However, EDS analysis of soil plasma in thin sections (Table 10) of the soils at the lowest position on the catenae exhibiting yellow and brown colors shows that the Fe_2O_3 concentrations are almost equal to those in upslope soils reflecting that these soils may contain much microcrystalline or amorphous iron (Eswaran, 1967; Stoops, 1968).

The element composition of the soil plasma was determined by EDS analysis at many points (up to 5-15 points per horizon) in thin sections (Table 10). Plasma of all soils on both catenae contains mainly Al_2O_3, SiO_2 and Fe_2O_3 reflecting the presence of kaolin and iron oxides. A relatively higher Si concentration in the ternary diagram is possibly due to very fine quartz distributed in the soil plasma. The high content of K_2O of soils in low positions on Nam Phong catena reflects the presence of illite which is present in high amounts in the toeslope soils. The valley floor soil on the Khon Buri catena has a relatively higher concentration of Mg than other basic cations associating with a presence of smectite.

Table 10 Average oxide elements concentration (%) in the soil plasma for Nam Phong and Khon Buri catenae

Depth	Horizon	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	CaO	MgO	MnO
Nam Phong catena									
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic								
0-20	Ap	25.17	53.00	10.03	2.45	0.51	6.09	1.15	nd
20-40	E	35.67	50.99	10.87	0.96	0.81	0.32	0.37	nd
59-73	Bt2	35.19	51.38	10.94	1.20	0.62	0.20	0.37	nd
105-142	Bt4	26.53	64.10	6.54	1.10	1.11	0.12	0.46	nd
172-205	Bt6	34.52	50.25	12.34	1.37	0.89	0.11	0.51	nd
	Shoulder: Psammentic Kandiustalf, sandy, siliceous, isohyperthermic								
0-23	Ap	8.97	86.83	3.32	0.32	0.41	0.00	0.15	nd
23-35	E	32.05	56.49	8.41	1.14	1.25	0.20	0.46	nd
35-58	Bt1	25.44	60.28	8.85	3.68	1.43	0.02	0.26	nd
58-82	Bt2	32.82	56.93	8.08	0.59	0.96	0.35	0.27	nd
82-110	Bt3	36.02	49.82	11.52	1.02	0.96	0.23	0.44	nd
140-190+	2C	36.05	49.34	11.44	1.07	1.06	0.35	0.69	nd
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic								
45-67	Bt1	27.14	61.27	9.10	1.07	1.06	0.00	0.36	nd
100-130	Bt3	28.79	60.20	8.13	1.12	1.27	0.10	0.39	nd
155-182+	Bt5	34.96	51.29	10.55	0.97	1.46	0.18	0.55	nd
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic								
46-63	Bt2	27.23	63.22	6.67	1.13	1.14	0.12	0.46	nd
80-100	2BC	37.77	48.94	10.74	0.82	1.19	0.00	0.53	nd
130-180+	2C	35.13	50.61	11.97	0.60	1.28	0.00	0.40	nd
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic								
20-30	Ap2	18.64	74.21	3.35	0.42	2.32	0.23	0.83	nd
30-45	Bw	14.05	65.54	11.86	1.42	1.48	0.90	0.84	nd
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic								
5-23/30	Btcg	27.19	52.53	13.47	0.78	3.57	0.69	1.72	nd
30-48	Btg1	25.13	50.16	17.18	0.70	4.01	0.73	1.95	nd
113-143	Btg4	21.88	63.79	6.16	0.50	4.15	0.78	2.25	nd
143-162	BCg1	25.03	57.13	9.07	0.31	4.61	0.70	3.06	nd
Khon Buri catena									
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic								
15-30	Ap	34.67	40.10	20.30	4.39	0.38	0.02	0.11	0.04
30-51	Bto1	36.13	41.98	18.20	3.58	0.04	0.00	0.08	0.00
130-160	Bo1	36.38	42.90	17.57	3.07	0.05	0.01	0.01	0.01
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic								
11-28/30	Ap	34.61	46.72	14.25	3.74	0.16	0.27	0.20	0.00
30-54	Bt1	35.09	41.96	15.82	3.52	0.28	2.66	0.51	0.15
59-88	Bt2	36.69	46.28	13.71	3.17	0.08	0.07	0.00	0.00
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic								
12-30	Ap2	29.27	45.32	22.53	1.72	0.25	0.26	0.33	0.33
50-72	Btc2	33.48	42.05	22.14	1.75	0.18	0.00	0.29	0.10
103-130	Btc4	32.61	47.25	17.06	2.52	0.33	0.01	0.20	0.03
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic								
0-15	Apg	26.94	51.49	17.05	2.15	0.39	0.61	1.38	0.00
76-100/110	Bg2	25.04	51.50	15.65	4.19	0.23	0.60	1.36	0.41
160-180	Crg	15.66	50.34	28.73	1.78	0.00	0.53	2.10	0.86

Up to 5-15 point in the soil plasma of thin section were analyzed by EDS analysis

2.3 2C-horizon of Soil on Shoulder and Midslope Positions on Nam Phong catena

The discontinuity of the C-horizon can be recognized in soils on shoulder and midslope positions on Nam Phong catena on the basis of both field and micromorphological feature. Their micrographs are shown in Figure 51. The 2C-horizons contain quartz, common chert and sandstone rock fragments. Quartz size is larger than those other soils on Nam Phong catena. Quartz grains are angular to subangular whereas quartz grains in other soils on Nam Phong catena are subrounded to rounded. They show a very strong red color of ferri-agrillan coated on quartz (thick laminated). In addition, they contain more fine material than the soils on shoulder and midslope positions. However, they are highly weathered which is indicated by the iron infilling in the quartz vein in the polycrystalline quartz.

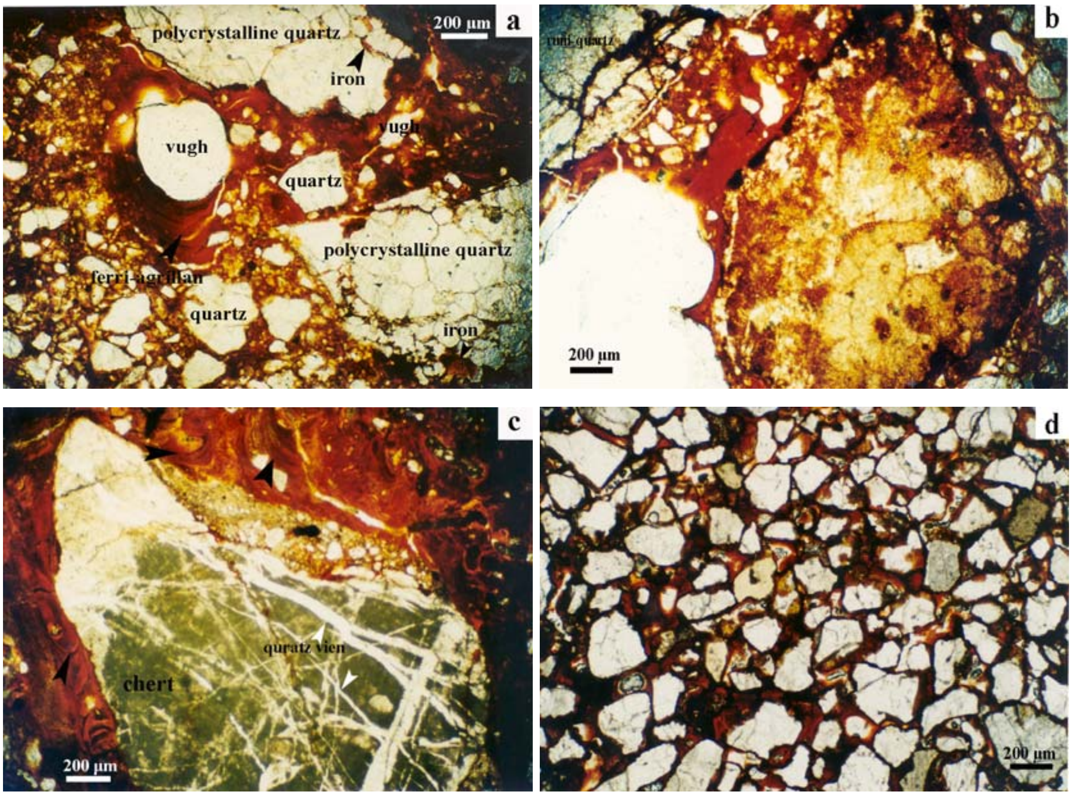


Figure 51 Transmitted light micrographs of a thin section of the 2C-horizon of Nam Phong catena showing thick laminated ferri-agrillan coated on quartz grains rock fragments and pore (a, b, c, d); iron filling in the polycrystalline quartz (a); weathered quartz (b); angular-subangular quartz, poorly sorted (a) and well sorted (d).

2.4 Cr-horizon of Soil on Footslope Position on Khon Buri catena

The Cr-horizon (weathered basalt) of footslope soils are shown in Figure 52. Plagioclase, olivine and hornblende are common in the weathered basalt. Olivine is incompatible with quartz for when excess silica is present during the differentiation of the magma, olivine combines with silica to form pyroxene (Eswaran, 1972). Where olivine is present in the solid rock, quartz is absent. Element mapping of the weathered basalt indicates that there is no quartz in the Cr-horizon. However, quartz is present in soils derived from basalt in Madagascar, Malaysia, Thailand and Ireland (Eswaran, 1972).

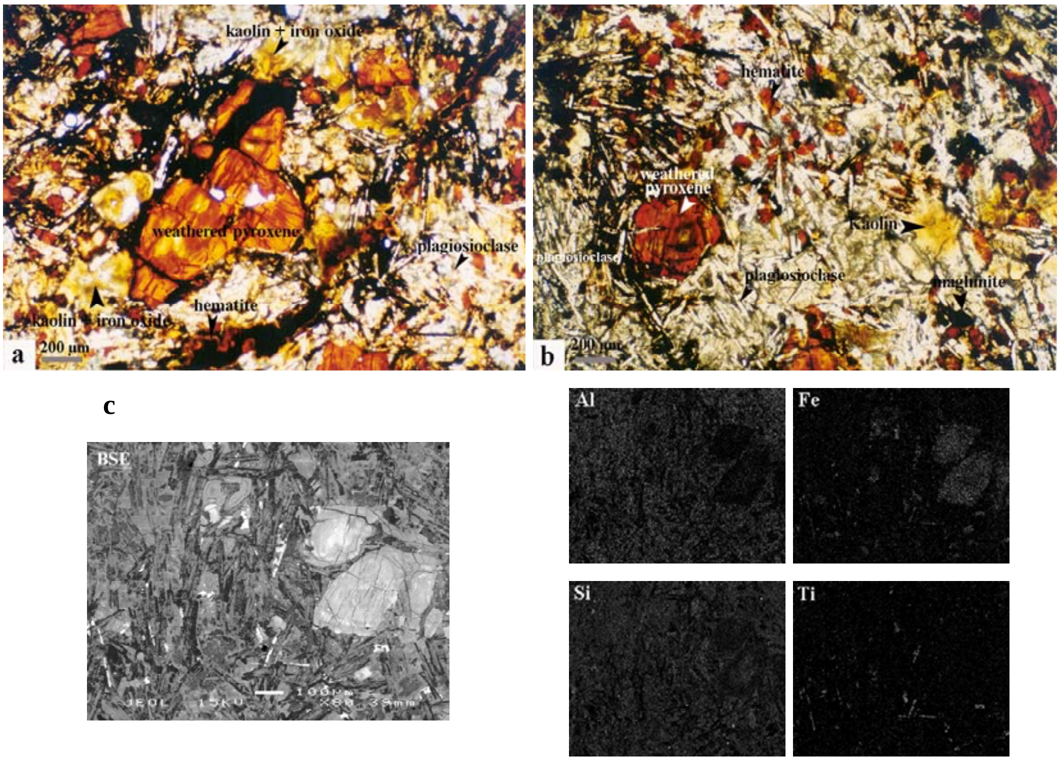


Figure 52 Thin section photographs (a, b) and element mapping (c) of weathered basalt (Cr-Horizon) showing groundmass of lath shape microcrystalline of calcic plagioclase feldspar with minor amount of pyroxene, olivine and maghemite; Al, Fe, Si and Ti mapping of the weathered basalt.

3. Authigenesis of Minerals

3.1 Quartz

SEM backscatter micrographs of upslope soils on Nam Phong catena (Figure 53) show pores and voids in the soils resulting from between sand grains. There is a loose arrangement of sand and silt particles with interparticle voids in various diameters for surface soils. The packing of the silt particles among sand particles increases in the subsurface horizon.

As shown in Figure 53 soils on Nam Phong catena contain much quartz. BSE images of the upslope soils (Figure 48) show the various sizes and shapes of quartz. There is a little evidence of rounded sand grain increases downslope. Most of quartz grains are broken possibly reflecting their colluvial origin (Tapakul Na Ayutthaya, 1994). Several forms of quartz in the upslope soils on Nam Phong catena are shown in Figure 53. In thin section, types of quartz include chalcedony, chert and quartz crystals. Quartz is present in polycrystalline, runi-polycrystalline, crystal growth and cutan forms. The presence of polycrystalline quartz indicates the soil to be derived from metamorphic rocks (Asumadu *et al.*, 1979). The extensive dissolution of silica can occur along cracks and intercrystalline boundaries in strained and polycrystalline quartz grains (Little *et al.*, 1978). Sometimes secondary cracks exist in the quartz and become filled with iron oxides. By the time crystallization reaches the center, the soil solution becomes under saturated with silica and as a result the quartz formation is present as cutan (Eswaran, 1972). These suggest that the upslope soils on Nam Phong catena are derived from sedimentary rock, mainly sandstone mixed with metamorphic rocks.

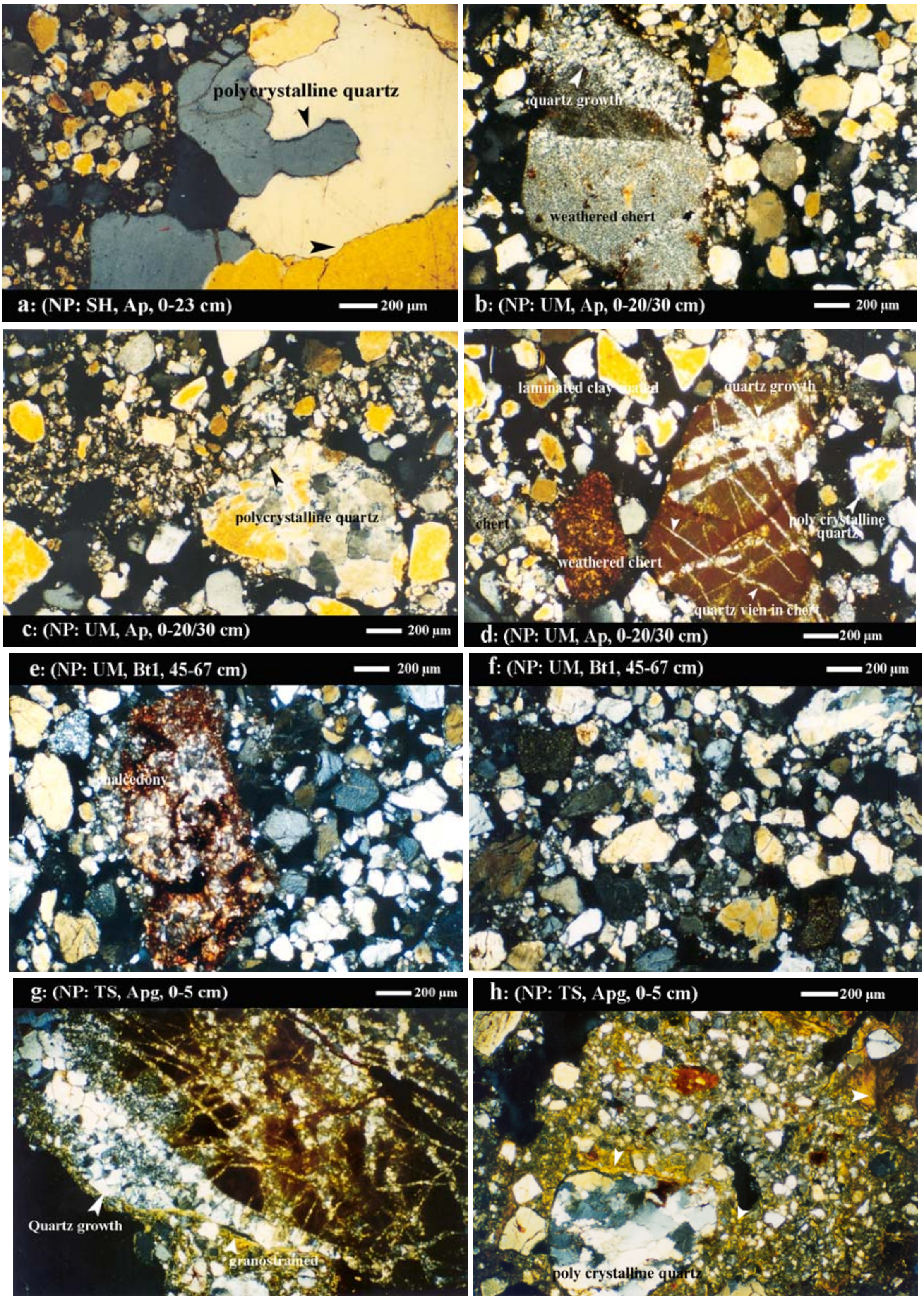


Figure 53 Micrographs of a thin section of soils on Nam Phong catena under cross polarized light showing the various quartz forms: poly crystalline quartz (a, c, f, g), quartz growth in chert vein (b, d, g), quartz growth from polycrystalline quartz (c), runi-polycrystalline quartz (e), secondary quartz as cutan (h).

3.2 Lithorelict

The lithorelicts are large and numerous in footslope soil which decreases in size and number towards the surface, but there are few in the soil on backslope position. On Khon Buri catena the lithorelict in soils is almost completely transformed but there are some weathered pyroxene and weathered plagioclase feldspar grins (Figure 54). In most cases, the lithorelicts are extremely enriched by sesquioxides due to the formation of secondary minerals such as goethite, hematite and kaolin. The neoformation of kaolin can also occur in the weathering of lithorelicts (Eswaran, 1972).

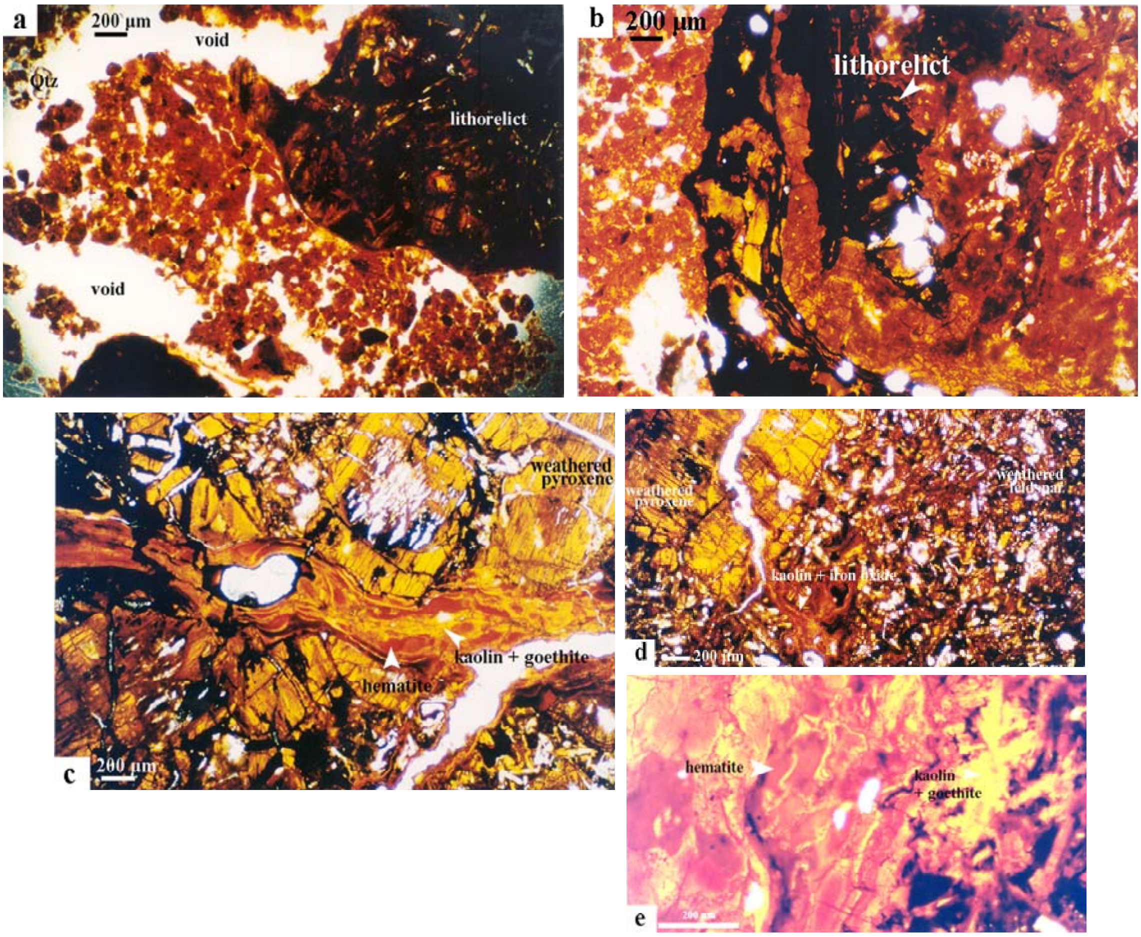


Figure 54 Transmitted light micrographs of thin section of the lithorelict present in the footslope position of Khon Buri catena showing; the lithorelict almost completely transformed (a, b) giving goethite, hematite and kaolinite; (c, d, e) the detail of lithorelict.

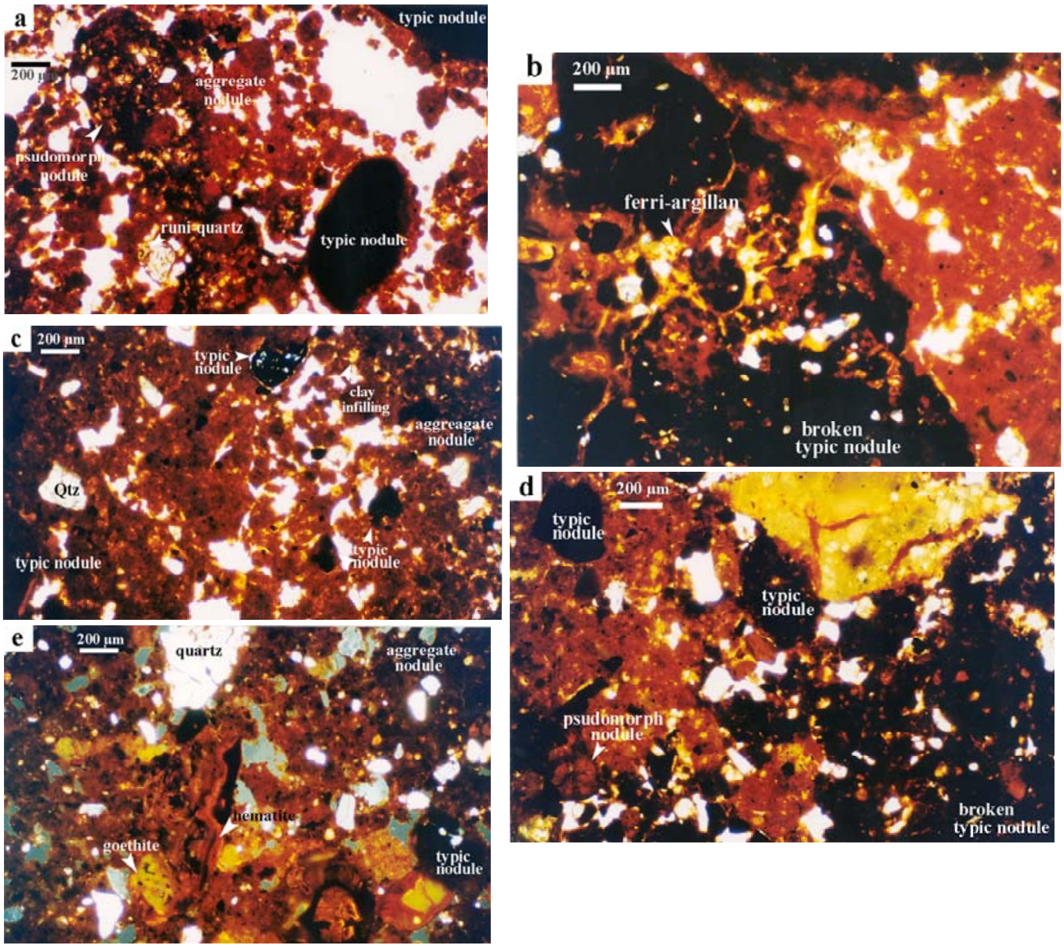


Figure 55 Transmitted light micrographs of thin section of soils on Khon Buri catena showing various nodule types; typic nodule (a, b, c, d, e), broken typic nodule (b, d), aggregate nodule (a, c, e), psudomorph nodule (d).

3.3 Iron Oxide Nodule

Typic nodules and psedomorphic nodules are present in all soil positions on both catenae. Also iron impregnative nodules commonly occur. Various nodule types occur in large amount in soils on Khon Buri catena due to the iron rich mineralogy of the parent rock. Nodules in soils on Khon Buri catena are shown in Figure 55. There is sharp boundary between typic nodules and soil matrix. The iron impregnated nodules, typic and aggregate nodules, and mottles present in the soils are associated with the oxidation-reduction process (Brewer, 1964).

3.4 Pedogenic Carbonate

The carbonate impregnated nodules, recrystallized carbonate and carbonate impregnated s-matrix occur only in the soils on the lowest position on landscape and they are present only in the deep horizon of soil on the valley floor position of Khon Buri catena (Figure 56). The carbonate comes from groundwater which in the dry season forms carbonate nodules (Pal and Deshpande, 1987; Kalbande, 1992). These soils have high pH (pH> 8).

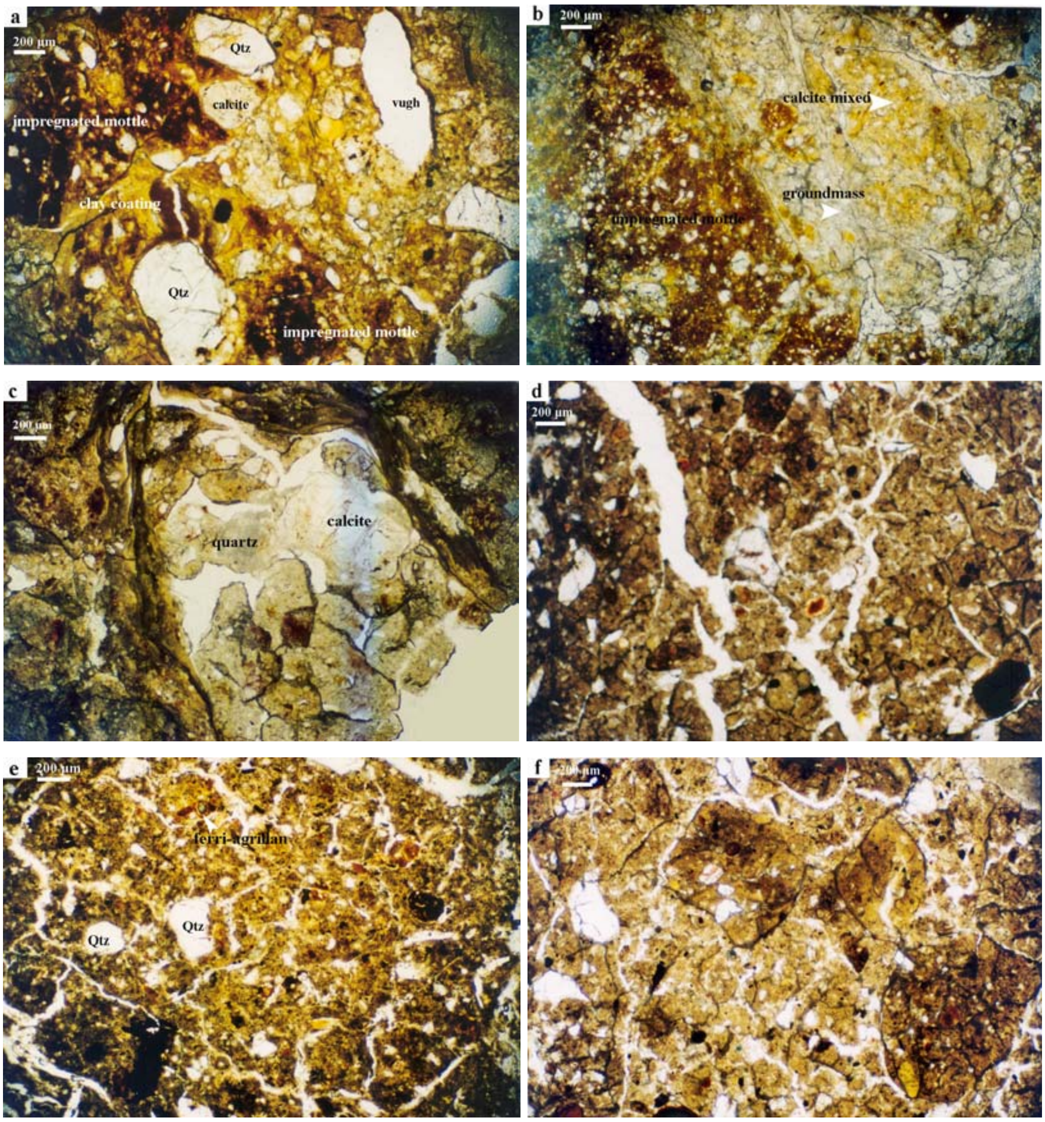


Figure 56 Transmitted light photographs of thin section of soils on the toeslope position of Nam Phong catena (a, b, c) and on valley floor position of Khon Buri catena (d, e, f).

4. **Synthesis**

For Nam Phong catena, bridged grain structures are mainly microstructure of soils on summit and shoulder, single grain structure is well expressed in soils on midslope and footslope, subangular blocky structures are predominant in toeslope soil. A presence of bridged grain structure and clay coates on pore walls and quartz grains is interpreted as an indicator of highly developed soils especially soils on the summit and shoulder positions. The major voids of upslope soils are simple packing voids along with few vughs, chambers and vesicles. Planar void is a major void in the toeslope soil. The coarse textured soils on all positions contain mainly quartz grains, runi-quartz, polycrystalline quartz and chert, few sandstone rock fragments and chacedony, and rare amounts of anhedral zircon and tourmaline. The dominant pedofeature as clay mixed with iron oxides coated on pore walls and quartz grains in soils on the high positions indicate illuviation and eluviation processes. Microlaminated ferri-agrillan coating is clearly observed in 2C-horizon along with angular and subangular quartz with larger size. This confirms a discontinuity of the soil parent materials on the shoulder and midslope positions. In addition, the carbonate impregnated nodules and recrystallized carbonate in toeslope soil reflect a high pH. These lead to a conclusion that upslope soils are derived mainly from weathered sandstone along with meta-sedimentary rock whereas the toeslope soil derived from fine grain sedimentary rock possibly be shale.

For the soils on the Khon Buri catena, crumb and granular structure are major microstructures of crest soil, subangular blocky structure is mainly microstructure for backslope and footslope soils. Soil on the valley floor has subangular blocky structure and locally with crack structure. The compound packing void is mainly void in the upslope soil whereas planar void is mainly void along with few vughs and channel voids in valley floor soil. The c/f related distribution are open porphyric for the soils on all positions in the catena due to the nature of soil parent materials. The coarse material of soils on this catena contains mainly quartz grain, common runi-quartz and rare zircon and weathered pyroxene. However, in soils on the backslope and footslope positions, the weathered pyroxene slightly increases with depth. This indicates that soil on the crest position is more weathered than soils on the backslope and footslope positions. In addition, the highly weathered basalt rock fragments (lithorelicts) are observed, increasing with depth in the soils on the backslope and footslope position. The clay fragments and clay infilling are present in all soils on this catena. Typic nodules and psedumorphic nodules are common in the soil on the backslope and footslope positions. The few typic nodules and aggregated nodules are found in soils on the valley floor position. These further indicate that all soils on this catena are formed on basalt (Eswaran, 1972; Jongmans, 1993). In addition, the carbonate impregnated nodules are found only in the deep horizon of soil on the valley floor position where low rate of leaching can be envisioned.

Quartz Sand Grain Size and Surface Morphology for Nam Phong and Khon Buri Catenae

The surface texture of quartz sand grains in soils has been studied by many researchers for various purposes, including identifying the origins and weathering history of soil materials (Krinsley and Donahue, 1968; Hurst, 1981; Mazzullo and Magenheimer, 1986; Mazzullo *et al.*, 1992; Xiao *et al.*, 1995; Helland *et al.*, 1997). The weathering intensity in soils may be revealed by surface rounding, etching or overgrowth on quartz grains (Crook, 1968; Darmody, 1985; Asumadu *et al.*, 1987; Pye and Mazzullo, 1994; Marcelino and Stoops, 1996; Marcelino *et al.*, 1999).

Scanning electron microscopy of surface features on quartz grains may assist with the environmental reconstruction of the sedimentary history of sand. The diverse surface features are open to a wide range of interpretations but have been commonly used to identify the provenance and transport mechanism of soil materials. Various chemical and mechanical processes produce surface textures which can either be original, resulting from crystallization and post magmatic change occurring in rocks or can result from mechanical and chemical alteration of grains after liberation from the parent rock (Doornkamp and Krinsley, 1971; Asumadu *et al.*, 1979). Douglas and Platt (1977) proposed that in general the surface texture of quartz grains becomes more complex with soil age. Some caution must be observed as grain surface features usually associated with one weathering or transport process may be produced by other processes and sample treatment may introduce artifacts (Krinsley and Doornkamp, 1973; Darmody, 1985).

The most typical chemical surface features on quartz grains in tropical soils are v-shape or triangular etch pits (Krinsley and Doornkamp, 1973; Eswaran and Stoops, 1979; Asumadu *et al.*, 1987). Pye and Mazzullo (1994) noted that silica dissolution and grain etching takes place particularly in the podzolic A-horizon under conditions of high rainfall, low soil pH (3.0-4.5) and a high concentration of organic acids derived from acidophyllous dune vegetation cover. Marcelino *et al.* (1999) found that quartz in soil at the summit position was less weathered than at other soil positions in a catena of soils in Rwanda. This was explained as being due to differences in drainage condition due to topographical position. Well drained soils on slopes are more intensely leached and thus experience stronger chemical weathering, which is reflected in the presence of more triangular etch pits and chatter marks on the surface of quartz grains. In the case of an imperfectly drained soil on a valley bottom the dissolution of quartz is inhibited by oversaturation in silica in the drainage water and deposition of secondary silica may occur. Precipitation of silica can be very important in altering the surface morphology of sand grains in residual materials (Douglas and Platt, 1977). Quartz grains liberated from crystalline rocks are highly nonspherical, have angular outlines and sometimes have crystalline faces. These grain features are the results of crystallization and deformation at elevated temperature and pressure. Quartz grains from cemented sedimentary rocks often have a moderately angular outline and well defined quartz overgrowths (Mazzullo and Magenhiemer, 1986). Quartz sand grains from ancient soils under tropical climate may have severely altered surfaces and interiors due to them having reached advanced stages of the various dissolution and precipitation processes (Little *et al.*, 1978).

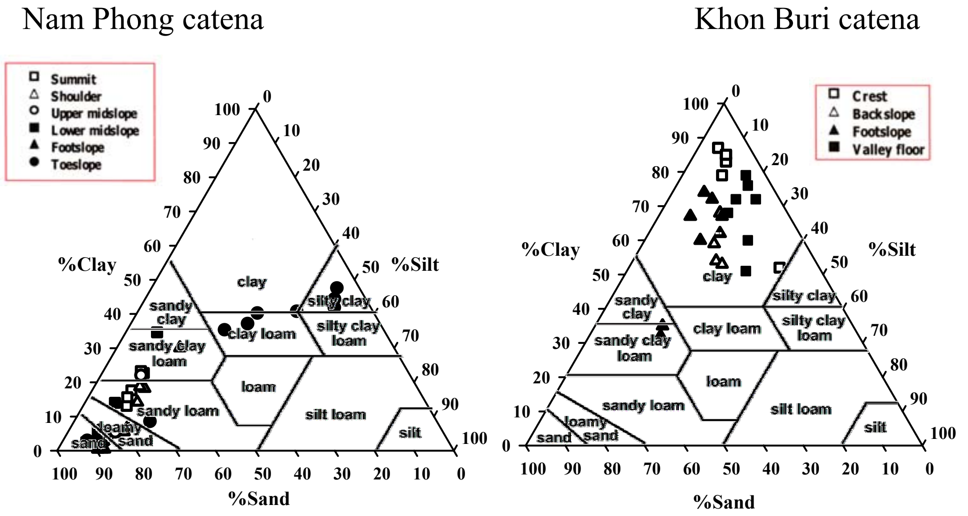
V-shaped impact pits, conchoidal breakage and ridges can be produced by mechanical abrasion during transport (Hurst, 1981). Eswaran and Stoops (1979) attempted to relate conchoidal feature to sedimentary environments including conditions under which the grain was dislodged from the rock prior to transport and sedimentation. Wind transported grains may have highly rounded outlines and abraded grain surfaces which are the product of collision. River transport and turbidity currents do not impress characteristic features on grain surfaces (Krinsley and Donahue, 1968).

In contrast to the extensive research on quartz grain surface features carried out on soils elsewhere, there has been little research on sand grains in soils in Thailand, especially in relation to soil genesis, one noticeable exception being the work of Prone (2003) who investigated sand grains from soil samples from an area in Northeast, Thailand. Hence, the specific purpose of this chapter is to study quartz sand grains and their morphology combined with an analysis of particle size distribution for the Nam Phong and Khon Buri catenae, Khorat Plateau, Thailand, to identify if this information provides an insight into soil genesis.

1. Particle Size Distribution in Soils on Nam Phong Catena

The graphical sorting parameters were used to characterize samples by providing a concise summary of particle size distribution and thus provide a basis for an interpretation of the environments of transport and deposition.

The particle size distribution data (Figure 57) for the several soils on the catena differ considerably which is consistent with variations in parent material and the action of colluvial transport processes on the catena. Soils from the summit to footslope have sand contents greater than 50% with textures ranging from sand to sandy clay loam. The high sand content is also present in the Ap-horizon of the toeslope soil, with sand content decreasing greatly with depth (Figure 58). Soils on all positions on the catena show a slight to strong increase of silt and clay contents and associated decrease of sand content with depth as is shown in Figure 58. There is evidence of the eluviation of fine material in the soil profiles on the summit, shoulder and toeslope positions but not for soils on midslope and footslope positions. These intermediate positions have highest slopes so that erosion occurs more quickly than elsewhere on the catena and the illuvial accumulation of clay is relatively less


Nam Phong catena

Khon Buri catena

Figure 57 Ternary graphs of sand, silt and clay concentrations for soils on Nam Phong and Khon Buri catenae.

important. The soil on the toeslope contains much silt and clay in subsoil horizons. The subsoil may have developed on residuum derived from fine grain sedimentary rock with the surface horizon (Ap1) being sandy colluvium. The profile particle size distribution plots also indicate a clear lithological break within the solum at the shoulder, midslope and toeslope positions (Figure 58). There is an abrupt increase in clay concentration from the Bt-horizon to the 2C-horizon. It is proposed that the shoulder, midslope and toeslope profiles consist of sandy colluvium over more clayey weathered shale but pedoturbation may have caused considerable mixing of materials.

The depth functions for graphical sorting parameters for the Nam Phong catena are shown in Figure 59. Mean size (Φ units) of profile samples decreases systematically downslope from summit to footslope position as larger sand sizes become more dominant. Mean size (Φ units) is much larger in the toeslope samples due to the very clayey nature of this profile. Sorting varies with depth for all profiles. The soils from the summit to the footslope are poorly to very poorly sorted with the exception of the three deepest samples in the toeslope soil which are quite well sorted. The generally poor sorting might be attributed to colluvial transportation and mixing into profiles of materials from upslope positions. All soil materials on this catena exhibit highly positive skewness with no consistent trends with depth or position on the catena.

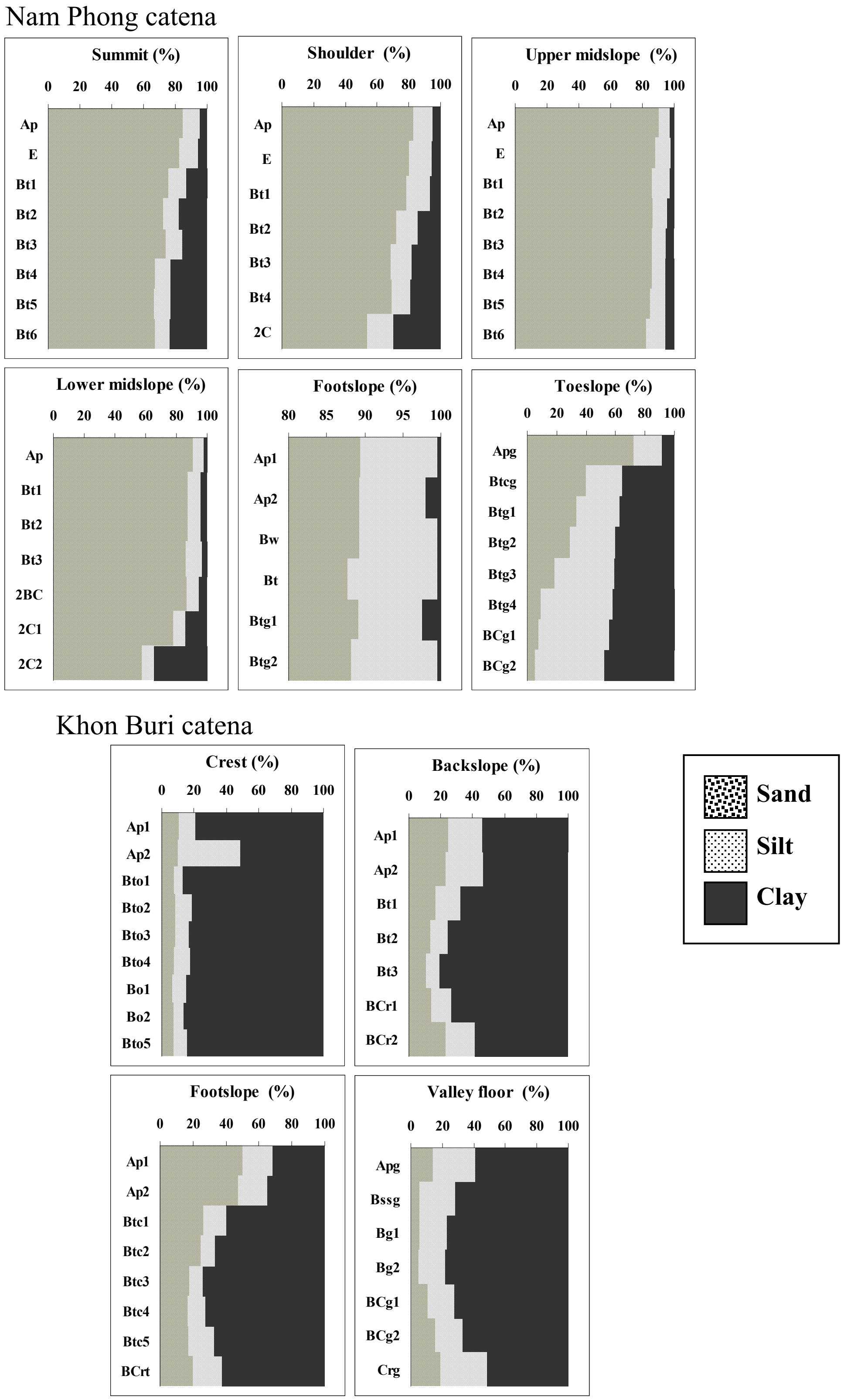


Figure 58 Profile distribution of sand, silt and clay for soils on Nam Phong and Khon Buri catenae.

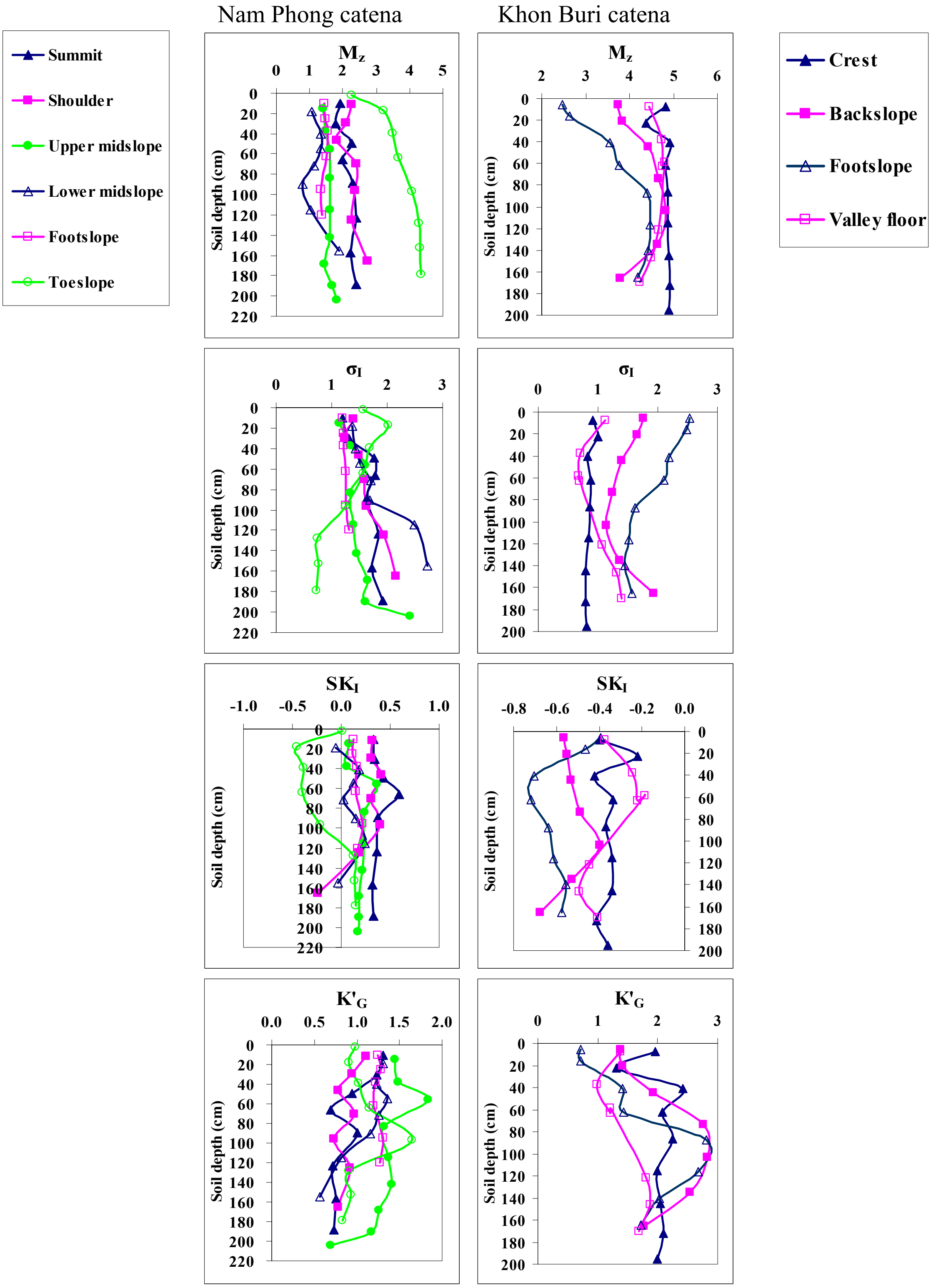


Figure 59 Grain size and sorting parameters (mean size (M_z), sorting (σ_I), skewness (SK_I) and kurtosis (K'_G)) for the soils of Nam Phong and Khon Buri catenae.

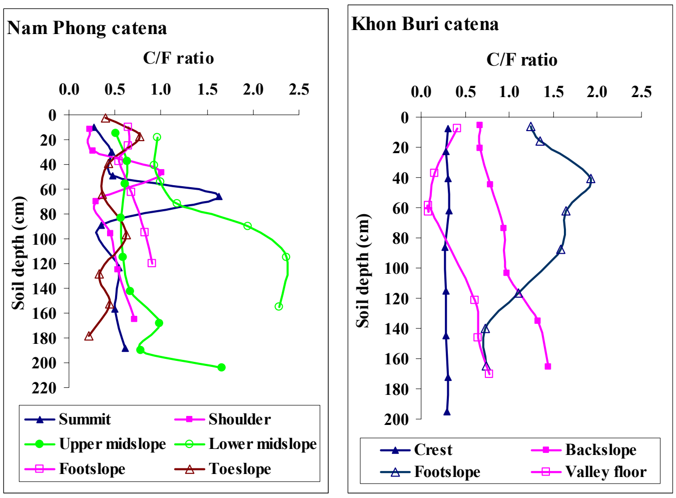


Figure 60 Depth functions for the coarse/fine sand (C/F) ratio for Nam Phong and Khon Buri catenae.

The coarse sand/fine sand ratio for Nam Phong soils (Figure 60) is somewhat variable and shows no systematic trend with depth except for the lower midslope profile where the ratio increases substantially in the lower part of the profile.

2. Particle Size Distribution of Soils on Khon Buri Catena

Soils on Khon Buri catena contain up to 30 percent quartz sand (Figure 57) which is inconsistent with the materials being derived solely from the weathering of (quartz free) basalt. Prone (2003) considers that aeolian transport of sand occurred in Northeast, Thailand during glacial periods and this process may have contributed quartz to Khon Buri catena. The major feature of the particle size depth functions for the Khon Buri catena is the pronounced clay bulge in subsoils of the backslope, footslope and valley floor profiles. The clay is mostly a result of weathering of basalt and the reduced clay percentages at the top and base of these three profiles are due respectively to colluvial addition of sand and eluviation of the clay from the surface soil, and the presence of sand and silt size partly weathered basalt grains in the deepest horizons. The crest profile shows a rather uniform distribution of materials with depth apart from an accumulation of silt or strongly aggregated clay in the Ap2 horizon. Figure 58 shows the distributions of sand, silt and clay for the soils for Khon Buri catena. The increasing concentration of clay with depth indicates that translocation of clay from the A-horizon to B-horizon has taken place. The high clay content of the B-horizon also indicates a moderate to high extent of transformation of the primary minerals in basalt to clay (Beckmann *et al.*, 1974).

The depth function for graphical mean size (Φ) (Figure 59) shows that mean size is mostly small (Φ>4) and there is no systematic trend in mean size with depth apart from the upper part of the footslope soil being notably coarse (smaller Φ). There are systematic differences in sorting between the four profiles with the footslope profile being more poorly sorted, especially in the upper part of the profile, which is again consistent with the admixture of exogenous material such as the aeolian sediment proposed by Prone (2003).

Both skewness and kurtosis vary considerably for all four profiles with the footslope soil exhibiting greatest skewness which is consistent with the colluvial admixture of coarse sand to a predominantly fine textured material.

The depth function of the coarse/fine sand ratio (Figure 60) is constant for the soil on the crest, is larger and quite constant for the backslope soil and quite variable for the footslope and valley floor soils. Values of the ratio are high (>1.8) for the upper part of the footslope soil which may be indicative of the admixture of coarse sand from another rock type.

The major reason for the thorough study of particle size and sorting for these catenae is to establish if materials are simply weathered residuum of underlying rocks or has there been admixture of exogenous material. This knowledge is essential to the interpretation of surface features of quartz grains. If the sand particles in these soils include introduced grains then differences in surface features between profiles or horizons cannot be confidently ascribed to only within profile chemical and physical alteration. The data presented in previous sections indicate that at least some profiles in both catenae are likely to include introduced sand grains but it is difficult to identify those samples that are similar or uniform in this respect.

A powerful statistical tool for comparing complex data sets is factor analysis. The data are reduced to a small number of variables (factors) that best discriminate

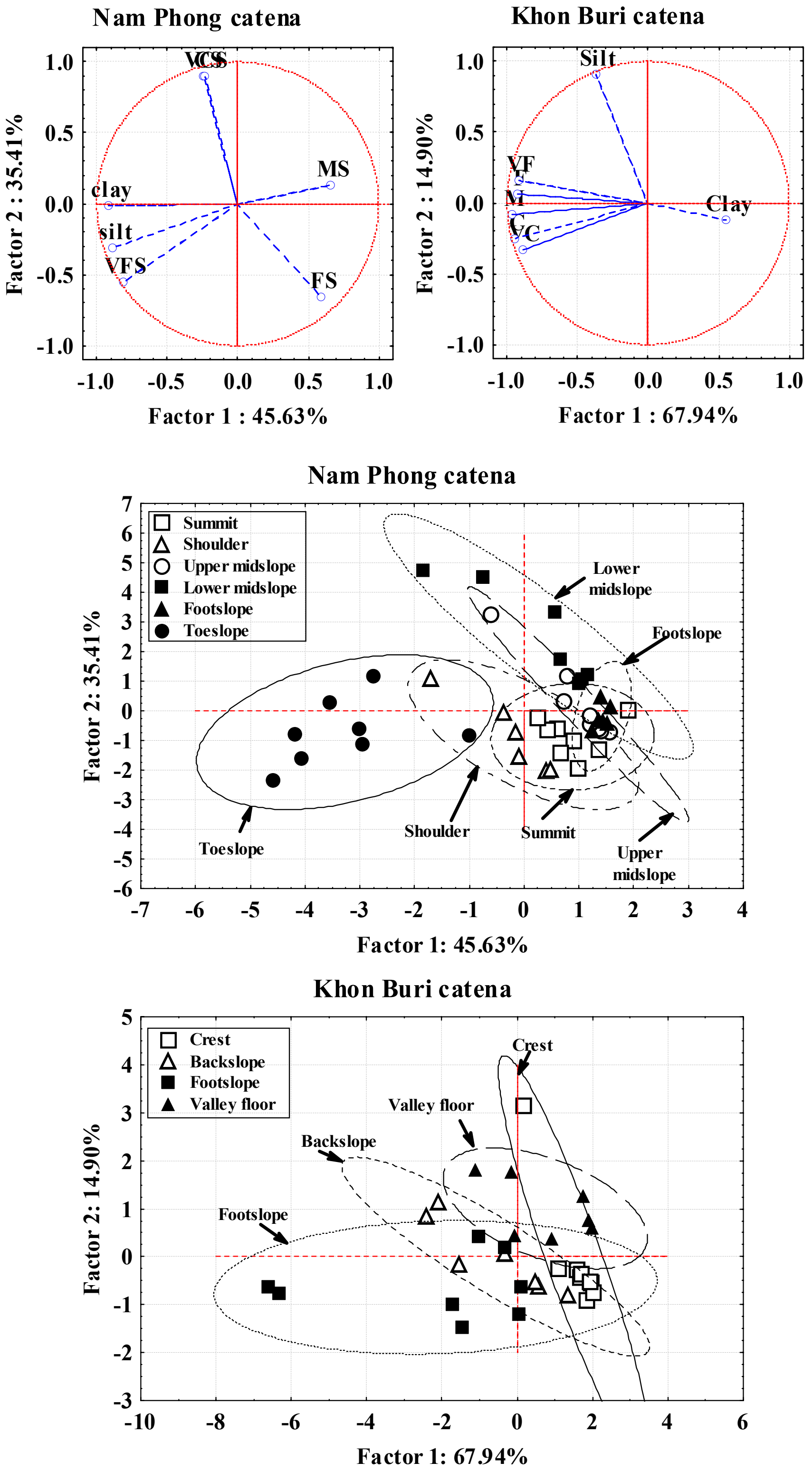


Figure 61 Factor analysis based on soil particle size distribution for Nam Phong and Khon Buri catenae. For the Nam Phong profiles some samples from the lower midslope and all samples from the toeslope are different from the remaining samples. For Khon Buri catena two footslope samples and one crest sample are very different from the remaining samples.

data sets. The particle size data (six size classes) were analysed in this way with outputs shown in Figure 61 being used to test for uniformity of materials. For Nam Phong catena most of the materials are rather similar apart from B and C horizons of the lower midslope profile, and 2C horizons of the shallower and upper midslope profiles which may therefore contain quartz from exogenous sources. All of the toeslope materials are quite different from the other profiles in this catena. For Khon Buri catena, all samples are quite similar apart from Ap1 and Ap2 horizons of the footslope soil which are distinctly different. This evidence indicates a uniformity of most materials within each catena and enables a more confident interpretation of the surface feature information discussed in the following section.

3. Quartz Sand Grain Surface Features

Scanning electron micrographs of representative surface features of quartz sand gains are given in Figures 62, 63 and 64. The nomenclature and interpretation of quartz surface features are based on the works of several researchers (Krinsley and Donahue, 1968; Krinsley and Doornkamp, 1973; Hurst, 1981; Asumadu *et al.*, 1987).

Three types of feature are recognized. Features characteristic of mechanical damage include surface roughness (Figure 62a), angular edges (Figure 62b), rounded edges (Figure 62c), conchoidal fracture (Figure 62d), cleavage plates (Figure 62e) and cracks (Figure 62f). Dissolution features include etch pits (Figure 63a), v-shape pits (Figure 63b), triangular pits (Figure 63c) and solution striae (Figure 63d). Precipitation features include silica precipitation (Figure 64a), silica plate and sheets (Figure 64b), plastered amorphous silica (Figure 64c), adhering particles (Figure 64d), crystal growth (Figure 64e) and authigenic quartz (Figure 64f). Together these features reflect the various transport and chemical weathering processes that take place in soils and can be used to differentiate the extent of grain surface modification and dominant alteration processes at each position on the catena. All of these features occur in soils in Northeast, Thailand and have been interpreted by Prone (2003) as indicating a complex provenance for soil material. The types and abundance of surface features on fine sand grains of selected horizons on Nam Phong and Khon Buri catenae are summarized in Tables 11 and 12.

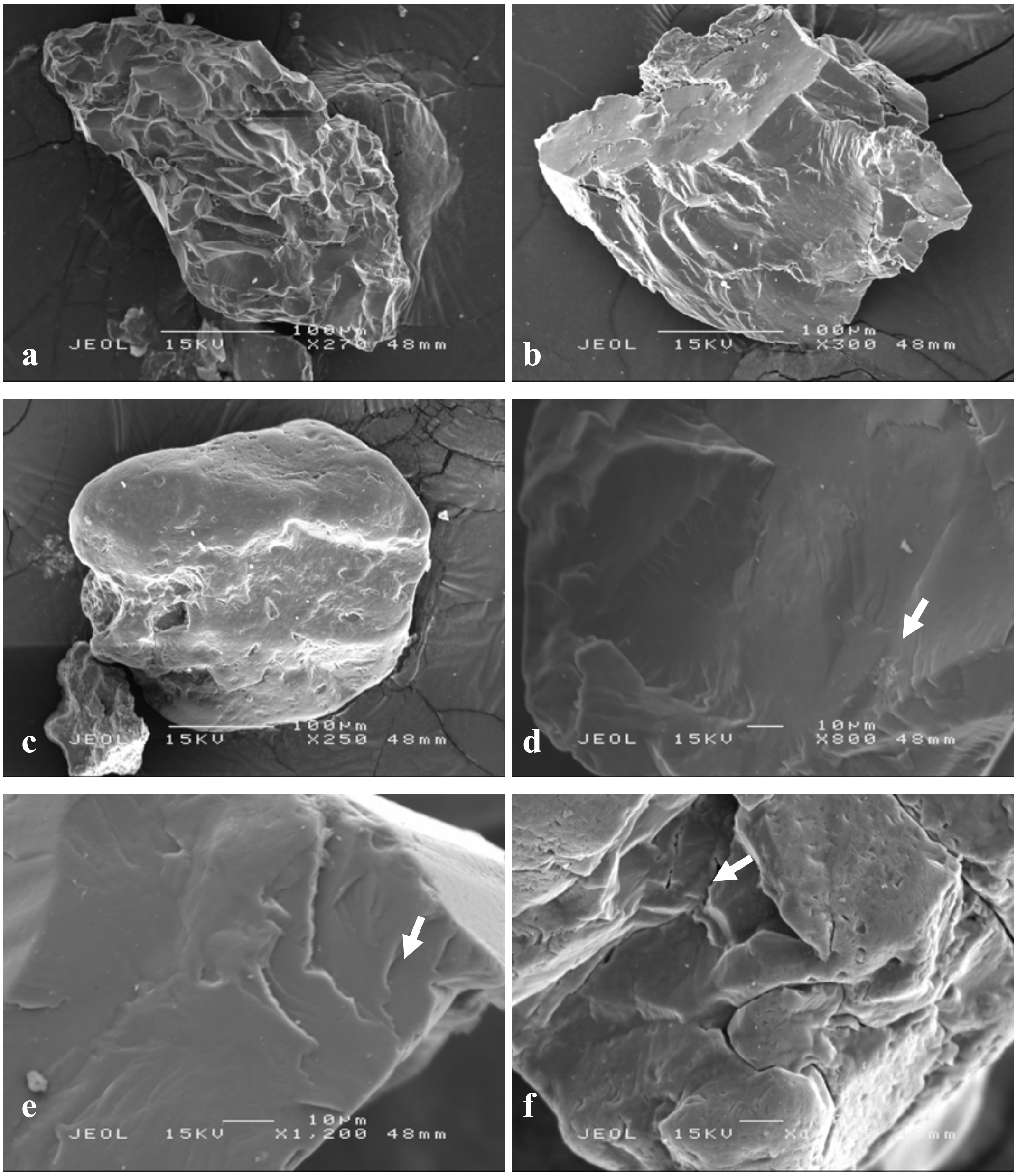


Figure 62 SEM secondary electron micrographs of quartz grains showing (a) rough surface; (b) angular edge; (c) rounded edge; (d) conchodial fracture; (e) cleavage plate and (f) crack (the arrows show specific features).

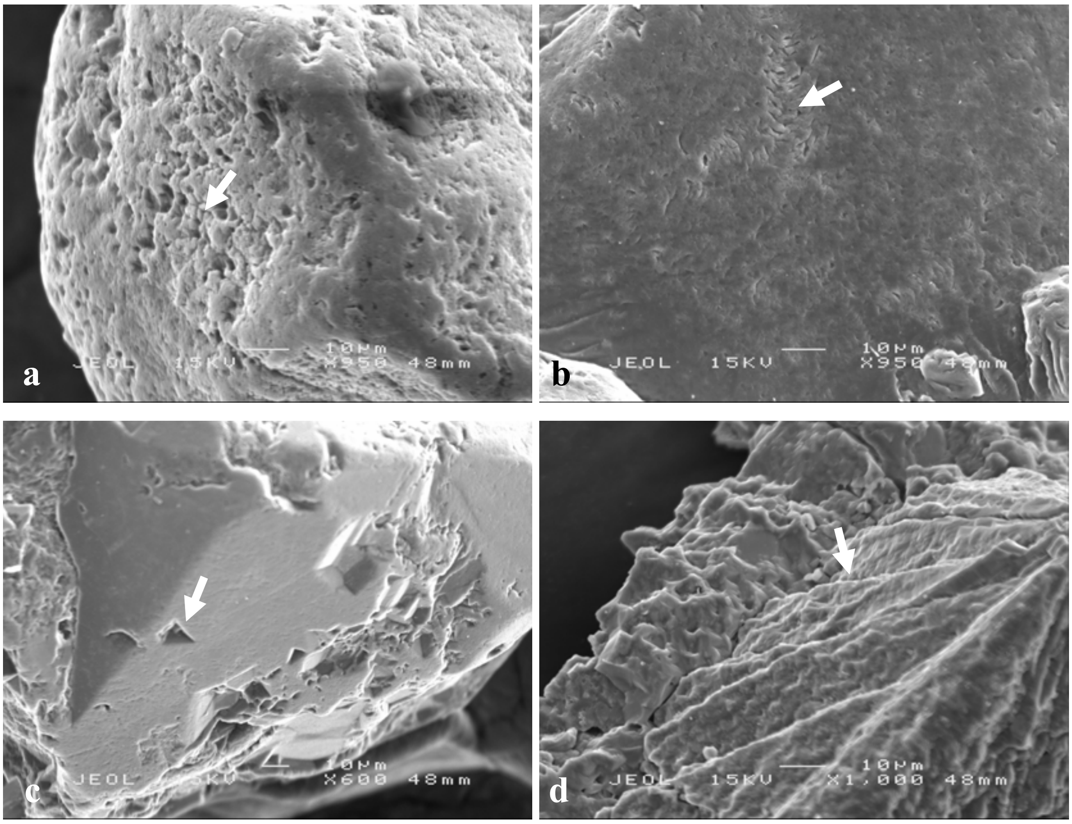


Figure 63 SEM secondary electron micrographs of quartz grains showing (a) etch pits; (b) v-shape pits; (c) triangular pits; (d) striae (the arrows show specific features).

It is evident from Table 11 that all possible surface features commonly occur on quartz grains from sites on the Nam Phong transect, with the exception of authigenic quartz which was present in minor amounts in only one sample from the summit. The various features indicate that physical change, dissolution and precipitation of silica have affected quartz grains from the entire catena. However there are no distinct trends in the abundance of features along the catena or down profiles. Consequently firm conclusions on pedogenesis cannot be determined.

There may be a weak trend towards the more common occurrence of etch pits in the upper part of the catena which in consistent with the stronger leaching condition of the higher sites.

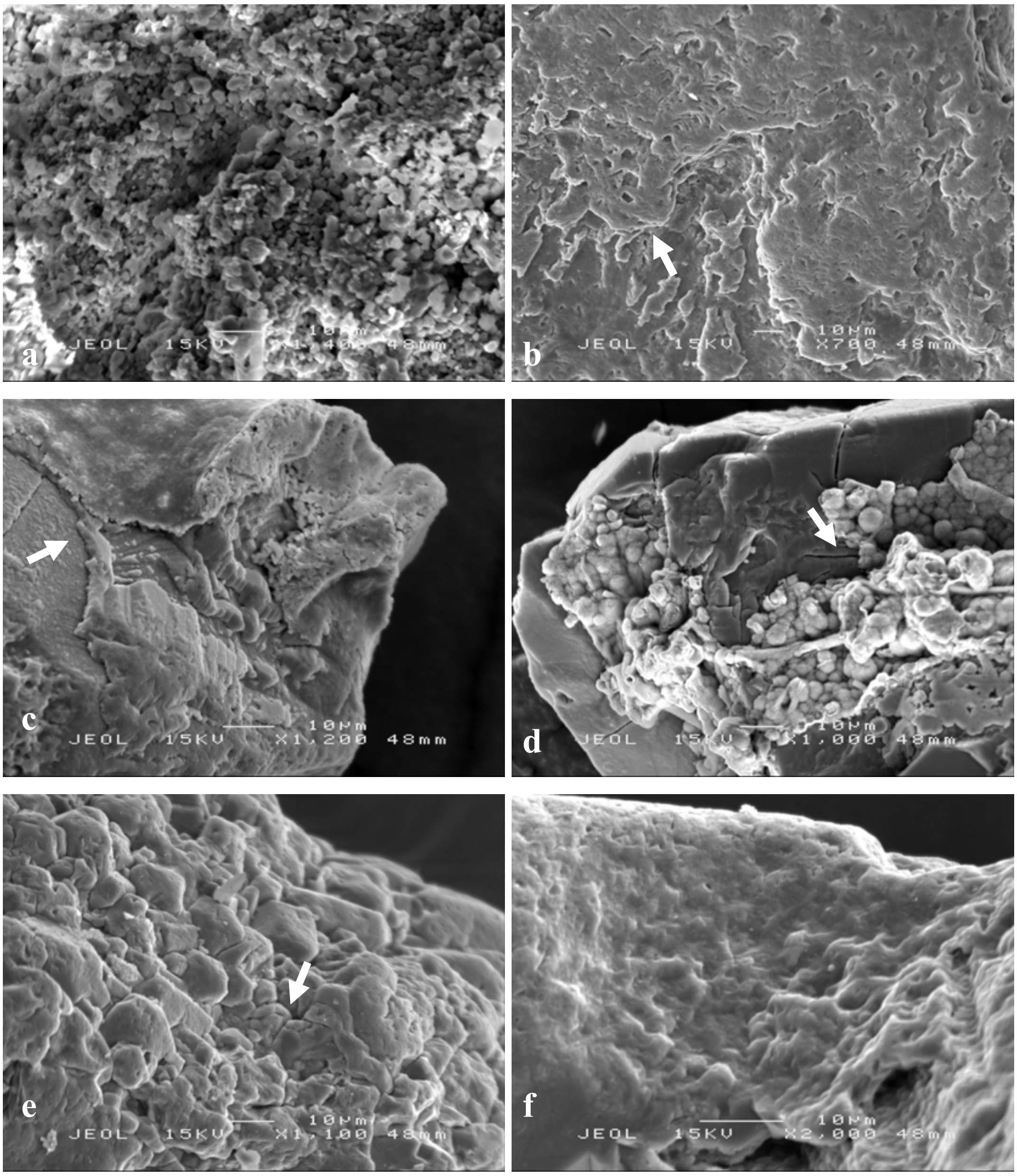


Figure 64 SEM secondary electron micrographs of quartz grains showing (a) silica precipitation; (b) silica plate; (c) plastered amorphous silica; (d) adhering particle; (e) crystal growth and (f) authigenic quartz (the arrows show specific features)

Table 11 Summary of quartz sand grain surface features in soils on Nam Phong catena

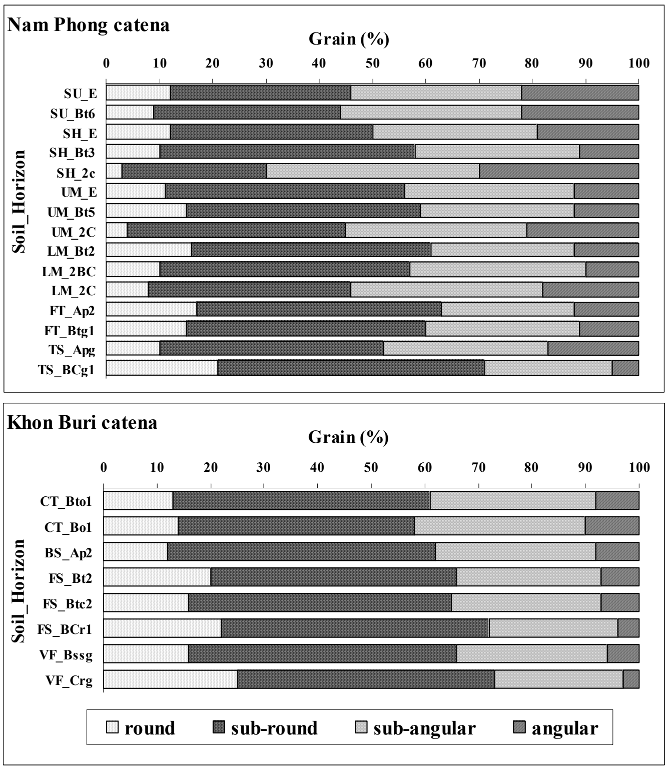
Feature / Profile horizon			Summit		Shoulder			Upper midslope			Lower midslope			Footslope		Toeslope	
			E	Bt6	E	Bt3	2C	E	Bt5	2C	Bt2	2BC	2C	Bw	Btg1	Apg	BCg1
Conchoidal	Transportation		░	▒	░	░	▒	░	░	░	░	☐	░	☐	░	░	☐
Rough surface			░	░	▒	░	▒	░	░	░	░	░	░	▒	░	☐	░
Angular edges			▓	▓	█	▒	█	▓	▓	▓	▓	▓	█	▓	▓	▓	▓
Rounded edges			▓	▓	▓	█	▒	▓	█	▓	▓	▓	▒	█	▓	█	█
Cleavage plate			░	▒	░	░	░	☐	░	░	☐	░	░	☐	☐	░	░
Crack			☐	☐	░	░	☐	☐	☐	☐	☐	☐	☐	☐	☐	░	░
Etch pit	Weathering	Dissolution	█	▓	▒	▓	▓	▓	▒	▒	▓	▒	░	▒	▒	▒	▒
V-shape pit			░	█	▓	▒	▒	▒	░	▒	▒	▒	░	▓	░	▒	░
Triangular pit			☐	░	░	█	░	☐	☐	☐	☐	░	☐	☐	☐	☐	☐
Solution line and striae			☐	░	▒	☐	▒	░	░	☐	░	☐	░	☐	☐	░	░
Silica precipitation		Precipitation	▒	▒	▓	░	░	▓	▒	▒	▓	▓	▓	▒	▒	░	▒
Silica plates and sheets			▒	▒	▒	☐	░	▒	░	░	░	░	☐	☐	░	▒	☐
Plastered amorphous silica			░	░	░	░	░	☐	░	░	☐	░	▓	░	░	░	▓
Adhering particle			☐	░	░	☐	░	░	☐	░	░	☐	▒	☐	░	░	▒
Crystal growth			▒	▒	▒	▒	░	▒	░	░	▒	░	▒	▒	░	░	░
Authigenic quartz			☐	░	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

☐ Absent ░ Few ▒ Present ▓ Common █ Abundant

Table 12 Summary of quartz sand grain surface features in soils on Khon Buri catena

Feature			Crest		Backslope		Footslope		Valley floor	
Profile horizon			Bto1	Bo1	Ap2	Bt2	Bt2	BCrt	Bssg	Crg
Conchoidal	Transportation		░	░	░	░	░	░	░	☐
Rough surface			▒	█	█	▓	▓	█	▒	▓
Angular edges			░	░	░	░	▓	░	░	░
Rounded edges			▓	▓	▓	▓	▓	█	█	█
Sub-rounded edges			█	█	▓	█	▓	▓	▓	▓
Crack			░	░	░	░	░	░	☐	▒
Etch pit	Weathering	Dissolution	█	▓	▓	▒	█	█	█	█
V-shape pit			▓	▓	▓	▒	▒	█	▒	▒
Triangular pit			█	▓	█	▓	▒	█	█	▒
Solution lines and striae			░	░	░	☐	░	░	░	☐
Silica precipitation		Precipitation	█	▓	▓	▒	▒	▒	░	░
Silica plate and sheets			▒	░	░	░	▒	▒	░	▒
Plastered amorphous silica			▓	░	░	░	▒	▓	▓	▒
Adhering particle			░	░	░	░	░	░	░	▒
Crystal growth			▒	☐	░	☐	☐	☐	▒	☐
Authigenic quartz			☐	☐	░	☐	☐	☐	☐	☐

☐ Absent	░ Few	▒ Present	▓ Common	█ Abundant



Up to 100 grain per horizon were counted by using the SEM

Figure 65 Sand roundness classes for selected horizons of the Num Pong and Khon Buri catenae.

The quartz sand grain surfaces for the selected horizons of soils on Khon Buri catena are given in Table 12. The features are similar to those for Nam Phong catena. Features indicative of the dissolution of silica (i.e. etch pit, V-shape pit, triangular pit) are dominant in soils from all positions, however the soil on the valley floor has the lowest frequency of silica dissolution features. The abundant rounded and sub-rounded edges observed in soils for all landscape positions indicate that transportation rounding has taken place. This degree of rounding cannot be attributed to colluvial transport but is consistent with weathering dissolving sharp edges and also the introduction of exogenous rounded grains.

Descriptions of grain roundness used in this paper follow the nomenclature of Powers (1953). The roundness classes for quartz from selected soil horizons at each position are shown in Figure 65. Sub-rounded to sub-angular grains are dominant but there are no systematic differences between soil profiles or horizons for either catena.

4. Synthesis

Quartz sand grains in soils on Nam Phong and Khon Buri catenae exhibit a large range of surface features due to precipitation, dissolution and mechanical damage during transportation. Precipitation and dissolution features occur in soils at all positions on the catenae. Soils on Khon Buri catena have more dissolution features than those on Nam Phong catena. The hypothesis that differences in parent material and differences in weathering environment for the catena would be associated with clear, systematic differences in surface features is not sustained. Differences in particle size distribution within and between profiles are consistent with differences in parent materials, with differences being due to particle size sorting colluviation and authigenesis of clay in the lowest position on the catenary landscape together with the possible introduction of exogenous material, possibly the aeolian deposits proposed by Prone (2003). This discontinuity of parent materials at shoulder, upper midslope and toeslope positions on Nam Phong catena is consistent with the field morphology and particle size distribution. The principal component analysis also clearly indicates a discontinuity in soil materials at the shoulder and midslope positions on the Nam Phong catena. For the soils on Khon Buri catena, the principal component analysis, graphical sorting parameters and particle size distributions show the near uniformity of the parent materials within most of the profiles. All soils on this catena have a high clay content but the surface soil on the footslope has a high sand content due to deposited coarse material from upper positions in the landscape or possibly as alluvium.

For Nam Phong catena, the soils on the summit, shoulder, midslope and footslope have formed in colluvium over chemically altered sandstone while authigenesis of clay and carbonate has occurred in the toeslope soil. All soils on Khon Buri catena have been mostly derived from basalt but colluvial materials exist over *in situ* materials in this catena.

Pedogenesis Affects Mineralogical Trends on the Catenae

The mineralogy in the sand, silt and clay fractions, dominant mineral characteristics, and minerals transformation in the soils on both catenae are discussed under this heading with an emphasis on their mineralogical trends as affected by tropical pedogenesis.

1 Mineralogical Trend on Nam Phong Catena

Under the optical microscope, most soils on Nam Phong catena contain much quartz of various types (i.e. polycrystalline quartz, chert, chalcedony), indicating they are derived from sandstone except the soil on the toeslope. Therefore, these soils are characteristic coarse-textured soils. In the case of the soil on the toeslope position, its parent material is quite different from that of the other soils. It contains much more clay and also pedogenic carbonate throughout the soil profile. However, the surface horizon has much coarse material including polycrystalline quartz than do the deeper horizons. This might indicate that this soil is formed on residuum derived from shale overlain by transported sandstone derived material.

Considering the mineral component in the silt and sand fractions, all soils comprise only quartz (Table 4) which inherited from their parent material. The veins in quartz grains and broken quartz indicate that quartz sand grains were transported from the upper positions on the landscape. The mechanical features (such as conchoidal feature, rough surface and rounded edge) on the quartz sand grains also mildly support this transported conditions. In the case of the toeslope soil, the quartz content in the surface soil is much higher than in the subsurface horizons. This also confirms the movement of material from the higher position.

Kaolin-vermiculite-illite clay mineral sequence is present in clay fraction of soils on this catena (Figure 66). Kaolinite tends to decrease, in contrast, illite and vermiculite tend to increase downslope associating with microenvironment on each

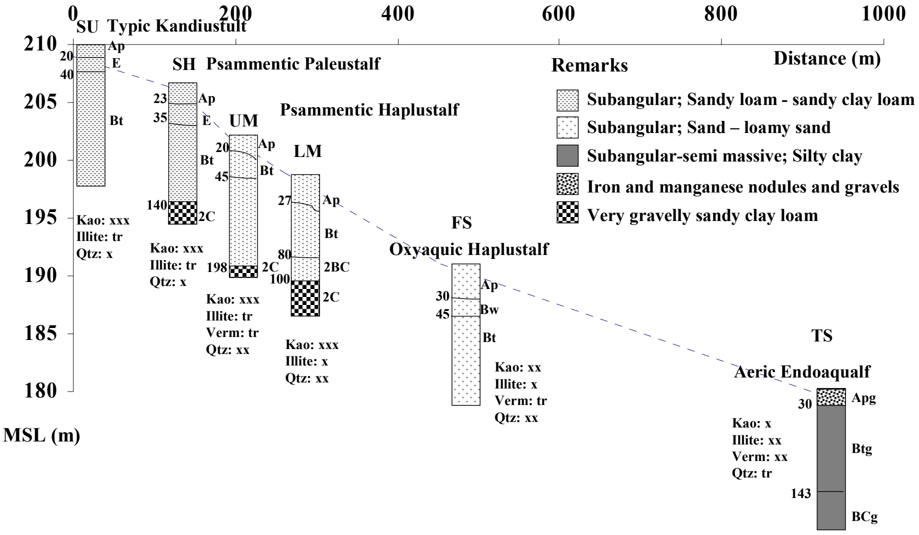


Figure 66 Soil morphological model with a semi-quantitative mineralogy (kaolin (Kao), vermiculite (Verm), illite, quartz (Qtz)) of the clay fraction on summit (SU), shoulder (SH), upper midslope (UM), lower midslope (LM), footslope (FS) and toeslope (TS) positions of Nam Phong catena.

landscape position. Soils on upper positions of the catena experience high leaching, base depleting environment resulting in the formation of kaolin (Vijarnsorn and Fehrenbacher, 1973; Gallez *et al.*, 1976; Boonsompoppunth, 1981; Suddhiprakarn *et al.*, 1985). The basic cations are released from the primary mineral that might be mainly feldspar and leached from the soils on upper slope position to accumulate in the lowest position on the landscape where the poorly drained condition prevails. This attribute the alkaline condition in toeslope soil with high K concentration suited for the illite formation (Fanning *et al.*, 1989). In addition, an increase of illite coupled with the decrease of vermiculite within the toeslope profile support a possibility of illite formation from vermiculite transformation by water table fluctuation (Sroden and Eberl, 1984).

2. Mineralogical Trend on Khon Buri Catena

Based on their field morphological and micromophological characteristics, all soils on Khon Buri catena can be considered to have derived from colluvium or/and

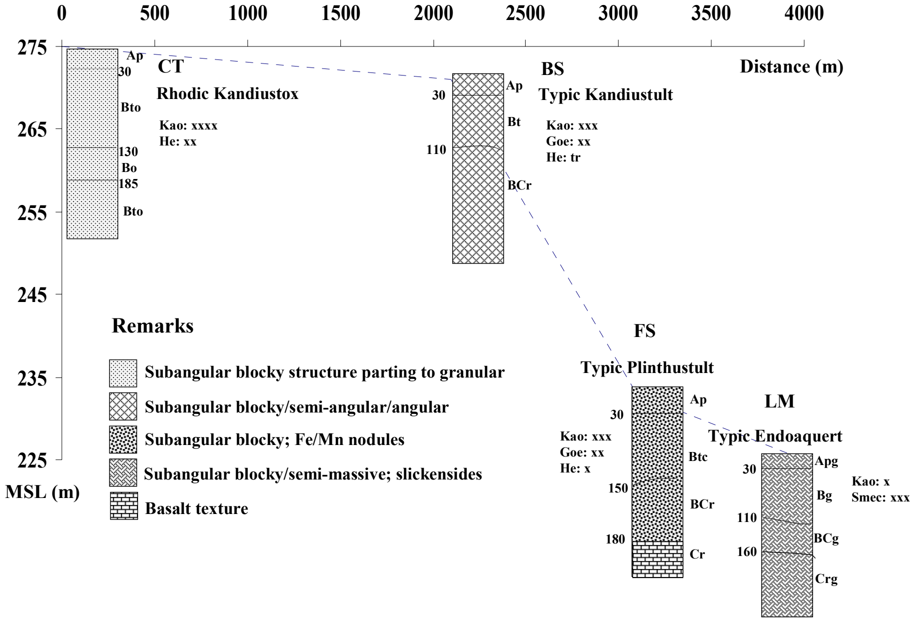


Figure 67 Soil morphological model with a semi-quantitative mineralogy (kaolin (Kao), smectite (Smec), hematite (He), goethite (Goe)) of the clay fraction on crest (CT), .backslope (BS), footslope (FS) and valley floor (VF) positions of Khon Buri catena.

residuum of basalt. The mineralogy of their silt and fine sand fractions is dominated by quartz (Table 5). Though quartz is not commonly a significant constituent of basalt (Mackenzie and Adams, 1994) the large amounts of quartz can be interpreted as authigenic particularly on the lower part of the catena (McKeague and Cline, 1963; Singer, 1967; Eswaran, 1971).

Kaolin dominates the clay fraction in the three upslope profiles with abundant smectite in the valley floor soil (Table 5). For the iron oxide mineral, the crest soil contains only hematite while both goethite and hematite are present in soils on the backslope and footslope positions. Goethite occurs only in the near surface horizons of the valley floor soil.

The mineralogy trend of the clay fraction on Khon buri catena is shown in Figure 67. Kaolin-smectite clay mineral sequence is attributed by the difference in intensity of weathering on each landscape position. The early stage of weathering under poorly drained environment produces a base rich environment with limited leaching condition induces smectite formation. A mature stage of weathering under well drained condition provides an oxidizing condition, inducing formation of kaolin and iron oxide from primary minerals or smectite. The transformation of smectite to kaolin is induced by the loss of bases especially Mg under acid environment (Harder, 1972; Prudeneio *et al.*, 2003). At the very high stage of weathering under well drained condition, only kaolin and iron oxides prevail since all smectite transformed to kaolin and most of iron oxides are found as hematite due to the drier condition of this position.

3. Comparative Mineralogy Trends between Nam Phong and Khon Buri Catenae

Soils on Nam Phong catena have texture ranging from loamy sand to silty clay whereas soils on Khon Buri catena are clayey as influenced by their parent materials. The systematic spatial distributions of minerals in clay fraction found on both catenae are kaolin as the major clay mineral of the upslope soils while 2:1 clay minerals dominate clay fraction of the soil on the lowest position with the influence of concentration of potassium and magnesium. A presence of hematite and goethite in the upslope soils reflects intense weathering and their occurrence is controlled mainly by redox conditions and pedoclimate. Only little amount of goethite is present in soils at low position where poorly drainage prevails, reflecting a seasonally reduced and iron oxide-poor environment. Leaching and eluviation-illuviation are considered the main pedogenic processes in the soils on the higher positions whereas cumulization is the major pedogenic process in the lowest position of both catenary sequences. In addition, there is an oxidation-reduction environment related to soil drainage condition influencing type of iron oxide mineral and soil color.

4. Synthesis

Mineralogical trends on Nam Phong and Khon Buri catenae systematically show that kaolin is the major clay mineral of the upslope soils whereas 2:1 clay minerals dominate clay fraction of the soils on the lowest position. This clearly shows the effects of relief on soil development on both of catenae. The relief provides variation of environmental conditions occurring on landscape related to mineralogy change. Dominant characteristics of upslope soils are acidic condition with low exchangeable bases which favors the kaolin formation. Soils on the lowest positions are alkaline, having high exchangeable bases due to accumulation of leached bases from the upslope soils inducing the 2:1 mineral type formation. The soils on higher positions with a well drainage showing the highest development are controlled mainly by leaching and eluviation-illuviation processes. The soils on the lower positions where poor drainage prevails are less developed as influenced by water activity. The soils on the midslope of the landscape with steeper slopes having intermediate characteristics are controlled mainly by erosion. Collectively, leaching and eluviation-illuviation are mainly pedogenic processes in soils on the higher positions while cumulization is the major pedogenic process in soils on the lowest position of both catenae. A presence of hematite and goethite reflects the intense weathering and their occurrence is controlled mainly by redox conditions and pedoclimate. An oxidation-reduction environment related to soil drainage condition influences type of iron oxide mineral. However, mineralogical data of the soils on Nam Phong catena which derived from different parent materials indicate more influence of parent materials on soil development and their properties particularly on the type of clay and the amount of their clay content.

CONCLUSIONS

Nam Phong Catena Derived from Sedimentary Rock

All soils on Nam Phong catena classified according to Soil Taxonomy (Soil Survey Staff, 1999) are Typic Kandiustult, Kandic Paleustalf, Typic Haplustalf, Oxyaqic Haplustalf, Aeric Endoaqualf for soils on summit, shoulder, midslope and footslope and toeslope positions respectively. All soils on this catena are deep. The textures of upslope soils range from sandy to loamy sand for surface soil and sandy to sandy clay loam for subsurface horizon whereas the textures of toeslope soil range from silty clay to clay loam. The red color gradually decreases downslope. Upslope soils experience continuous well drained condition, hence red to dark red color with no mottles prevail. The toeslope profile is at the lowest position on the soil sequence. It is poorly drained and the soil has a yellow color and many mottles which is consistent with its wet environment. Iron and manganese oxide nodules occur at 5-30 cm depth in the toeslope soil due to seasonal redox variations associating with the fluctuation in water table of this soil position.

The upslope soils have a lower bulk density than those of toeslope soil which are possibly due to the movement of fine materials down to the lower position on the landscape. The water retention of upslope soils are mostly in the macropore and little in the mesopore and micropore reflecting risks of insufficient water in some cultivated season. For the toeslope soil, the water content can remain in the macropore, quite equally to that in the mesopore and micropore which make it suited for paddy cultivation. The upslope soils are acidic. The basic cations have been leached from the upslope soils and accumulate in soils on the toeslope position. This attribute alkaline condition in toeslope soil with higher basic cations corresponding to the high CEC.

In addition, there is an abrupt change in materials from the Bt-horizon to the 2BC or 2C horizon of soils at the shoulder and midslope positions with a presence of various sizes up to 3 cm rock fragment gravels in the 2BC or 2C horizon (i.e. a stone line). Hence, discontinuity of parent material is recognized in both field and micromorphological feature at shoulder and midslope positions.

Kaolin is the major clay mineral in the upslope soils whereas illite dominates the clay fraction of the toeslope soil. Hematite can be found only in the summit soil while goethite is found in all soil positions except in the toeslope soil which is influenced by redox condition and pedoclimate. Only quartz is detected by XRD in the silt and fine sand fraction for all soils on this catena.

Soils at all positions contain much Si, together with minor Al and Fe. The major elements are closely related to minerals present in soils. The element compositions of upslope soil show little variation and the chemical compositions of upslope profiles overlap closely. However, the chemical composition of the toeslope soil is distinctly different from that of the soils on higher positions where a wide variation in chemical component exists. The small variations in the chemical composition of upslope soils are due to the different degrees of weathering of the same parent rock, whereas soil on the toeslope position has a quite different elemental composition which is due to both a difference in composition of the parent rock and formation of authigenic minerals.

Quartz is the major constituent shown in the thin section of upslope soils associated with bridged grain and single grain microstructures and also simple packing voids. Microstructure of toeslope soil is subangular blocky with planar void. Various forms of quartz including polycrystalline quartz, runi-quartz, chalcedony, chert and sandstone rock fragment are recognized in soils on this catena. Clay mixed with iron coating on pore walls and quartz grains present in these soils indicate illuviation and eluviation. Microlaminated ferri-agrillan coating is clearly observed in 2C-horizon along with angular and subangular quartz of larger sizes. This confirms a discontinuity of the soil parent materials on the shoulder and midslope positions. In addition, the carbonate impregnated nodules and recrystallized carbonate are found only in toeslope soil reflecting a high pH condition.

These systematic results lead to an interpretation that upslope soils on Nam Phong catena have formed on colluvium derived from sandstone mixed with metamorphic rock over chemically altered sandstone while authigenesis of clay and carbonate has occurred in the toeslope soil.

Khon Buri Catena Developed on Basalt

The soils classified according to Soil Taxonomy (Soil Survey Staff, 1999) are Rhodic Kandiustox, Typic Kandiustult, Typic Plinthustult and Typic Endoaquert for the four positions on crest, backslope, footslope and valley floor respectively on Khon Buri catena. All soils on this catena are deep. The soil on the crest shows the highest weathered condition and highest development on this catena confirmed by a presence of granular structure, a dark red color throughout the soil profile and a little evidence of clay translocation within the soil profile. Cracks are well expressed in both surface and subsurface horizons of the valley floor soils; slickensides and pressure faces are common in this soil. Many iron and manganese nodules occur throughout the soil profile on the footslope position whereas only a few iron and manganese nodules are present in the lower part of the soil on the backslope position. Changes of soil color from dark red on the upper slopes to dark olive gray on the valley floor within Khon Buri catena are obvious in the field.

The upslope soils have a lower bulk density than does the valley floor soil. Water retention of the upslope soils are mostly remaining in the macropore and little in the mesopore and micropore. For the valley floor soil, water remains in the macropore, quite equally to that in the mesopore and micropore. The upslope soils have a quite uniform chemical properties within the profiles whereas the valley floor soil varies widely in the profile chemical properties as shown by the factor analysis. Dominant chemical characteristics of the upslope soils are acidic condition related to the low basic cation content while the alkaline condition is associated with the high extractable bases, especially Ca and Mg in the soils on the lowest position on this catena. These results reflect the CEC increases downslope which attribute the leached cations moving to the lowest position on the landscape.

The dominant mineral in the clay fraction of the upslope soils and the valley floor soil are kaolin and beidellite respectively. Quartz is the major constituent along with trace of hematite, goethite and anatase in the silt and sand fractions of soils at all positions on Khon Buri catena. The crest soil contains only hematite while both goethite and hematite are present in soils on the backslope and footslope. Goethite occurs only in the near surface horizons of the valley floor soil where hematite is absent.

The crest soil is the most weathered, having uniform Al, Si, Fe and Ti concentrations and very low amounts of Ca, Mg and K throughout the profile. Kaolin and iron oxide minerals are major constituents with little quartz and no weatherable minerals present in this soil. Backslope and footslope soils are also highly weathered soils and they have similar Al, Si, Fe and Ti distribution patterns to those in soil on the crest, but they contain higher amount of Mn in the Fe and Mn nodules. The valley floor soil is less severely weathered as it is on the lowest position of the landscape where there is a high water table and leached ions accumulation resulting in the authigenesis of smectite. The high amounts of Mg, Ca and K have been derived from weathering of basalt upslope. This geochemical environment has enabled feldspar to be preserved in the silt and fine sand fractions of the valley floor soil.

Crumb and granular are major microstructures of the crest soil, subangular blocky structure is mainly microstructure for backslope and footslope soils. Soil on the valley floor has subangular blocky structure and locally with crack structure. The void in the upslope soil is mainly compound packing void whereas planar void is found mainly in the valley floor soil. In addition, the lithorelicts are observed in the soils on the backslope and footslope position with an increasing trend with depth. The clay fragments and clay infilling are observed in all soils on this catena. Typic nodule and psedumorphic nodules are common in the soils on the backslope and footslope positions. The few typic nodules and aggregated nodules are found in soil on the valley floor. All soils on Khon Buri catena have been mostly derived from basalt but colluvial materials exist over residuum. In addition, the carbonate impregnated nodules are found only in lower horizons of the valley floor soil.

It is concluded that different extents and types of weathering have occurred in Khon Buri catena. Alteration of the basalt under a tropical climate has produced kaolin and iron oxide minerals as the dominant soil materials for well drained slope sites. The geochemistry of the soils mostly reflects this process. In the valley floor soil, the accumulation of leached ions has resulted in the crystallization of smectite and carbonate with their associated element suite.

Pedogenesis Affects Mineralogy of Soils on Nam Phong and Khon Buri Catenae

Mineralogical trends on the Nam Phong and Khon Buri catena are systematically observed as kaolin is mainly clay mineral of the upslope soils while 2:1 clay minerals dominate clay fraction of the soils on the lowest position. They clearly show the effects of relief on soil development on both of catenae. The relief produces variation of environmental conditions occurring on landscape which related to mineralogy change. However, the type of clay minerals on both catenae also reflects environmental conditions including moisture, concentration of cations in solution and the degree of weathering. At the lower position, the high base status derived from parent rock and the accumulation of leached ions from the upslope soils under poorly drained condition, induce illite and smection formation. In contrast, the intense weathering condition of soils at the higher positions on the catenae with base depleting environment under sufficient rainfall, high leaching and well drainage favors kaolin formation. Hematite and goethite are also the products of intense weathering and being controlled mainly by redox conditions and pedoclimate.

In conclusion, it is seasonable to postulate a hypothesis on pedogenic processes occuring in soils on these catenae. The soils on higher positions on the landscape with well-drainage show highest development as controlled mainly by leaching and eluviation-illuviation processes. The soils on the lower positions where poorly drainage prevails, are less developed as influenced by water activity. The soils on the midslope of the landscape with steeper slopes have intermediate characteristics as controlled mainly by erosion. Therefore, leaching and eluviation-illuviation are mainly pedogenic processes in the soils on the higher positions while cumulization is the major pedogenic process in the lowest position of both catenae.

However, considering the soils on Nam Phong catena which derived from different parent materials, it is clear that the parent material has a clear effect on soil development and their properties particularly on the type of clay mineral and the amount of their clay content.

APPENDIX

APPENDIX I

Appendix Table 1 Physical properties of soils on Nam Phong catena

Depth	Horizon	Sand					Sand	Silt	Clay	BD	AWC
		VC	C	M	F	VF					
		-- g kg^{-1} --								Mg m^{-3}	%
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic										
0-20	Ap	5	26	147	468	203	851	104	46	1.53	8.98
20-40	E	6	36	220	420	149	830	114	56	1.52	8.59
40-59	Bt1	11	45	188	374	140	759	110	131	1.49	7.51
59-73	Bt2	5	17	427	196	79	724	99	177	1.41	9.18
73-105	Bt3	10	38	146	393	158	745	99	157	1.34	8.72
105-142	Bt4	15	49	175	321	115	675	98	227	1.34	9.18
142-172	Bt5	15	54	154	325	120	668	105	227	1.45	9.32
172-205+	Bt6	18	60	177	283	134	672	95	233	1.61	9.88
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic										
0-23	Ap	12	25	115	434	245	832	118	51	1.55	7.21
23-35	E	9	25	131	418	220	804	141	56	1.57	7.40
35-58	Bt1	10	19	364	243	150	786	144	71	1.53	9.22
58-82	Bt2	19	34	112	352	210	727	131	142	1.50	8.85
82-110	Bt3	28	50	134	303	172	688	129	182	1.51	8.73
110-140	Bt4	47	66	128	284	173	697	115	188	1.61	9.70
140-190+	2C	92	58	75	176	138	540	159	301	1.93	nd
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic										
0-20/30	Ap	23	59	227	451	150	909	61	30	1.44	3.08
30-45	E	60	49	236	393	150	888	87	25	0.92	5.06
45-67	Bt1	19	51	257	390	147	864	106	30	1.51	5.04
67-100	Bt2	19	61	234	408	145	867	88	45	1.44	4.45
100-130	Bt3	24	63	231	389	154	862	88	50	1.46	3.91
130-155	Bt4	34	69	241	374	143	862	78	60	1.52	3.27
155-182	Bt5	71	107	244	303	126	851	94	55	1.55	3.14
182-198	Bt6	52	77	233	315	149	826	119	55	1.63	4.73
198-210+	2C	128	128	167	175	80	678	101	221	2.02	nd
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic										
0-27/35	Ap	84	114	250	352	115	914	61	25	1.49	2.76
35-46	Bt1	70	99	252	328	127	876	84	40	1.62	3.73
46-63	Bt2	69	104	262	323	117	874	86	40	1.64	4.69
63-80	Bt3	129	102	237	285	113	867	98	35	1.62	4.55
80-100	2BC	126	175	273	222	74	870	75	55	1.86	4.77
100-130	2C1	272	134	145	162	71	784	76	140	2.00	nd
130-180+	2C2	197	112	91	108	66	575	79	346	1.96	nd
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic										
0-10/20	Ap1	19	69	262	406	139	895	100	5	1.37	2.87
20-20/30	Ap2	26	66	258	397	147	894	86	20	1.55	2.53
30-45	Bw	18	62	234	406	174	894	101	5	1.48	2.95
45-80	Bt	25	67	264	380	142	878	117	5	1.42	3.27
80-110	Btg1	14	85	303	364	126	892	83	25	1.66	3.31
110-130+	Btg2	27	96	295	344	120	883	112	5	1.77	3.43
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic										
0-5	Apg	26	54	127	249	267	723	191	86	1.70	9.36
5-23/30	Btcg	65	48	61	100	127	401	245	354	1.77	10.52
30-48	Btg1	23	28	49	99	135	334	294	372	1.86	13.24
48-80	Btg2	10	22	47	95	120	294	303	403	1.68	10.66
80-113	Btg3	17	25	32	52	66	192	400	408	1.74	10.72
113-143	Btg4	3	6	14	28	41	92	489	419	1.66	12.05
143-162	BCg1	1	9	13	21	33	79	477	444	1.68	11.62
162-195+	BCg2	0	3	8	16	30	57	467	476	1.63	11.64

VC = very coarse sand (1-2mm), C = coarse sand (0.5-1 mm), M = medium sand (0.25-0.5 mm), F = fine sand (0.1-0.25 mm) and VF = very fine sand (0.05-0.1 mm)

BD = Bulk density

AWC = Available water capacity

Appendix Table 2 Physical properties of soils on Khon Buri catena

Depth	Horizon	Sand					Sand	Silt	Clay	BD	AWC
		VC	C	M	F	VF					
		-- g kg^{-1}							--	Mg m^{-3}	%
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic										
0-15	Ap1	42	58	152	473	353	108	100	792	0.97	8.13
15-30	Ap2	34	57	139	477	336	105	380	516	1.25	8.55
30-51	Bto1	35	43	113	373	255	82	50	868	1.20	8.95
51-73	Bto2	40	43	121	380	266	85	103	812	1.17	9.93
73-100	Bto3	27	38	115	389	263	83	89	828	1.19	11.57
100-130	Bto4	32	40	106	371	263	81	95	824	0.98	9.43
130-160	Bo1	30	36	91	310	239	71	81	848	1.11	10.19
160-185	Bo2	41	35	93	312	233	71	65	864	1.08	9.34
185-205	Bto5	29	39	97	336	216	72	84	844	1.15	9.51
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic										
0-11	Ap1	255	319	433	856	641	250	210	540	1.01	12.80
11-28/30	Ap2	282	302	358	765	650	236	232	532	1.05	13.93
30-59	Bt1	296	226	226	524	433	170	154	676	1.09	12.85
59-88	Bt2	287	194	190	426	287	138	106	756	1.38	12.01
88-119	Bt3	271	119	130	302	233	106	87	808	1.32	11.19
119-151	BCr1	425	205	187	344	274	143	125	732	1.54	12.44
151-180+	BCr2	659	389	331	520	431	233	179	588	1.53	10.40
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic										
0-12	Ap1	1520	724	547	1259	984	503	177	320	1.47	10.40
12-30	Ap2	1339	788	618	1175	857	478	174	348	1.29	10.30
30-52	Btc1	1001	457	285	469	436	265	135	600	1.54	10.61
52-72	Btc2	793	489	276	424	523	250	82	668	1.46	9.98
72-103	Btc3	617	308	168	288	400	178	82	740	1.67	10.68
103-130	Btc4	495	240	147	336	465	168	108	724	1.65	10.14
130-150	Btc5	339	229	163	414	583	173	155	672	1.40	10.39
150-180	BCrt	313	285	247	554	592	199	177	624	1.15	9.67
180-197+	Cr									1.94	
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic										
0-15	Apg	175	107	140	462	550	143	265	592	0.84	10.89
25-50	Bssg	14	14	44	186	302	56	224	720	1.16	15.32
50-76	Bg1	6	10	28	149	363	56	176	768	1.17	14.64
76-100/110	Bg2	8	11	20	110	390	54	162	784	0.97	13.83
110-133	BCg1	143	116	145	367	297	107	169	724	1.10	13.52
133-160	BCg2	250	167	188	473	469	155	173	672	1.19	12.78
160-180+	Crg	379	219	219	549	510	188	296	516	1.18	13.78

VC = very coarse sand (1-2mm), C = coarse sand (0.5-1 mm), M = medium sand (0.25-0.5 mm), F = fine sand (0.1-0.25 mm) and VF = very fine sand (0.05-0.1 mm)

BD = Bulk density

AWC = Available water capacity

Appendix Table 3 Water retention (% wt.) of soils on Nam Phong and Khon Buri catenae

Depth	Horizon	Matric potential (kPa)								
(cm)		-0.1	-10	-33	-100	-500	-1500	-39000	-98000	-316000
		pF 0	pF 2.0	pF 2.5	pF 3	pF 3.5	pF 4.18	pF 5.6	pF 6.0	pF 6.5
						Nam Phong catena				
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic									
0-20	Ap	42.31	26.27	18.35	16.72	14.58	13.37	10.43	10.33	10.16
20-40	E	41.73	26.97	17.57	17.08	14.42	13.07	9.84	9.58	9.43
40-59	Bt1	39.41	24.78	15.14	14.14	13.81	11.44	10.44	9.75	9.41
59-73	Bt2	40.05	23.37	15.85	15.10	14.11	11.20	9.89	9.30	8.87
73-105	Bt3	40.32	24.33	16.48	14.69	12.39	12.06	9.03	8.67	8.05
172-205+	Bt6	39.13	25.03	16.79	15.43	14.42	12.01	8.28	7.64	7.30
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic									
0-23	Ap	44.84	28.24	18.03	16.80	15.19	14.10	9.63	9.44	9.24
23-35	E	40.97	26.96	19.17	17.61	16.16	14.85	9.99	9.68	9.51
35-58	Bt1	42.71	29.88	18.57	17.31	16.15	13.51	9.83	9.59	9.43
58-82	Bt2	43.93	30.95	18.25	17.15	15.88	13.36	8.61	7.93	7.73
82-110	Bt3	42.53	27.04	16.80	15.53	14.65	12.28	11.44	10.91	10.29
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic									
0-20/30	Ap	48.57	28.34	21.42	20.06	19.21	19.03	9.57	9.32	9.10
30-45	E	41.98	24.69	21.72	20.21	19.81	18.04	11.17	10.81	10.20
45-67	Bt1	52.23	32.56	24.87	22.92	21.97	20.45	12.16	11.82	11.47
100-130	Bt3	55.63	38.31	26.53	25.26	24.14	22.97	9.66	9.26	8.38
155-182	Bt5	55.18	41.63	25.95	25.34	25.01	23.02	11.58	11.06	10.70
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic									
46-63	Bt2	47.77	34.09	23.40	22.47	20.46	19.88	11.66	11.29	11.04
80-100	2BC	41.82	27.22	21.92	21.39	18.90	18.49	11.62	10.89	9.85
0-10/20	Ap1	49.69	31.56	23.28	22.31	21.52	21.05	11.34	11.02	10.71
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic									
20-20/30	Ap2	43.00	28.31	18.98	18.37	18.16	17.14	10.03	9.84	9.64
30-45	Bw	49.79	33.61	24.34	23.93	22.19	21.70	10.37	10.02	9.84
45-80	Bt	47.59	29.70	19.73	19.50	17.36	17.05	10.57	10.28	10.07
80-110	Btg1	45.58	31.23	20.66	19.15	18.40	18.06	11.20	10.73	10.46
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic									
0-5	Apg	49.58	30.85	24.18	18.44	16.95	16.71	10.65	10.11	9.66
5-23/30	Btcg	42.47	28.03	23.15	19.11	16.25	15.86	13.25	11.76	10.09
30-48	Btg1	44.32	29.76	25.76	22.62	17.71	16.69	12.85	11.42	9.59
48-80	Btg2	44.29	27.72	23.57	19.15	16.06	15.78	14.05	12.49	10.39
113-143	Btg4	45.72	29.86	26.12	20.82	17.97	17.36	14.19	12.65	10.46
143-162	BCg1	46.54	31.00	26.33	21.13	17.93	17.61	14.02	12.48	10.08
						Khon Buri catena				
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic									
0-15	Ap1	32.26	22.24	15.53	12.43	11.62	11.30	6.46	5.64	4.89
30-51	Bto1	33.35	25.32	17.70	14.27	13.63	13.28	7.42	6.67	6.02
73-100	Bto3	34.24	27.86	19.20	14.55	13.94	13.68	7.95	7.08	5.69
130-160	Bo1	34.32	26.80	17.75	12.94	12.42	12.20	7.01	6.20	5.39
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic									
30-59	Bt1	34.77	25.98	19.50	13.61	12.86	12.48	8.32	7.03	4.07
59-88	Bt2	34.22	23.73	19.28	13.96	13.25	12.80	7.28	5.35	3.46
119-151	BCr1	35.92	27.46	20.19	14.40	13.93	13.59	8.06	6.86	5.66
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic									
12-30	Ap2	38.10	29.54	20.66	16.53	15.31	14.72	10.43	8.70	6.96
52-72	Btc2	36.16	28.26	17.45	13.11	12.21	11.71	7.54	5.64	4.00
103-130	Btc4	36.07	27.50	17.46	13.58	12.78	12.26	7.74	5.93	4.20
150-180	BCrt	39.64	27.34	19.02	15.45	14.23	13.62	8.34	6.27	4.21
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic									
0-15	Apg	43.11	21.89	19.06	16.91	14.09	12.42	7.52	5.03	2.45
25-50	Bssg	46.96	32.00	27.21	23.54	19.67	17.34	10.58	7.12	3.69
76-100/110	Bg2	55.70	36.77	30.51	25.76	20.81	19.45	10.24	7.24	3.76
110-133	BCg1	54.19	33.30	27.12	22.96	18.60	17.38	10.51	7.90	4.17
160-180+	Crg	48.29	28.68	22.18	18.52	14.35	13.35	7.04	4.67	1.30

pF = log matric potential

<u>Appendix Table 4</u> Chemical properties of soils on Nam Phong catena

Depth	Horizon	pH		ΔpH	$CaCO_3$	OM	Total N	Avail. P	Avail. K	Extractable				Sum bases	Ex. Al	EA	CEC	CEC sum	CEC clay	ECEC	BS
										Ca	Mg	K	Na								
		H_2O	KCl		(%)	------ g kg^{-1}----		------- mg kg^{-1} ------		-- cmol kg^{-1}--											%
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic																				
0-20	Ap	6.30	4.80	-1.50	-	4.85	0.17	9.07	4.18	0.97	0.17	0.05	0.16	1.35	0.036	2.23	1.48	3.58	0.33	1.39	37.71
20-40	E	6.40	5.30	-1.10	-	1.64	0.07	1.00	4.04	0.74	0.15	0.05	0.19	1.13	0.001	1.49	0.90	2.62	0.16	1.13	43.13
40-59	Bt1	6.30	4.90	-1.40	-	1.37	0.11	0.90	2.31	1.18	0.19	0.03	0.11	1.51	0.008	2.23	3.31	3.74	0.25	1.52	40.37
59-73	Bt2	5.30	4.10	-1.20	-	1.65	0.02	1.01	3.49	1.21	0.28	0.05	0.04	1.58	0.137	2.23	2.26	3.81	0.13	1.72	41.47
73-105	Bt3	4.70	3.80	-0.90	-	1.68	0.11	1.00	3.70	0.16	0.42	0.05	0.06	0.69	0.578	2.23	1.56	2.92	0.10	1.27	23.63
105-142	Bt4	4.70	3.80	-0.90	-	1.68	0.09	0.76	4.00	0.81	0.93	0.05	0.05	1.84	0.658	3.73	2.32	5.57	0.10	2.50	33.03
142-172	Bt5	4.70	3.80	-0.90	-	1.68	0.07	1.01	4.44	0.08	0.56	0.06	0.07	0.77	0.673	3.73	1.41	4.50	0.06	1.44	17.11
172-205+	Bt6	4.70	3.90	-0.80	-	1.27	0.01	0.75	4.19	0.14	0.46	0.05	0.04	0.69	0.728	4.47	1.97	5.16	0.08	1.42	13.37
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic																				
0-23	Ap	6.60	5.50	-1.10	-	3.71	0.11	2.50	24.27	0.34	0.26	0.32	0.28	1.20	0.001	1.49	1.10	2.69	0.22	1.20	44.61
23-35	E	6.90	5.60	-1.30	-	1.31	0.05	1.05	35.25	0.13	0.08	0.46	0.10	0.77	0.001	1.49	1.15	2.26	0.21	0.77	34.07
35-58	Bt1	6.10	4.90	-1.20	-	1.83	0.05	0.90	45.41	0.20	0.08	0.59	0.37	1.24	0.018	2.23	0.70	3.47	0.10	1.26	35.73
58-82	Bt2	5.00	4.10	-0.90	-	1.78	0.06	1.36	23.78	0.87	0.40	0.31	0.31	1.89	0.091	2.23	2.31	4.12	0.16	1.98	45.87
82-110	Bt3	4.60	4.20	-0.40	-	1.91	0.07	0.91	5.73	1.07	0.90	0.07	0.11	2.15	0.061	2.98	2.37	5.13	0.13	2.21	41.91
110-140	Bt4	4.70	4.10	-0.60	-	2.35	0.11	0.76	5.43	1.57	0.80	0.07	0.16	2.60	0.089	2.98	5.54	5.58	0.30	2.69	46.59
140-190+	2C	5.00	4.60	-0.40	-	2.71	0.15	0.51	10.75	2.81	1.39	0.14	0.11	4.45	0.001	2.23	3.92	6.68	0.13	4.45	66.62
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																				
0-20/30	Ap	6.00	5.60	-0.40	-	3.73	0.10	6.11	7.06	0.95	0.37	0.09	0.03	1.44	0.006	1.49	1.15	2.93	0.38	1.45	49.15
30-45	E	6.30	5.70	-0.60	-	0.59	0.04	2.75	8.80	0.16	0.13	0.11	0.18	0.58	0.001	1.49	1.10	2.07	0.44	0.58	28.02
45-67	Bt1	7.00	5.80	-1.20	-	1.28	0.04	1.50	16.84	0.14	0.11	0.22	0.43	0.90	0.005	1.49	1.35	2.39	0.45	0.91	37.66
67-100	Bt2	6.60	5.20	-1.40	-	1.19	0.04	1.05	21.78	0.12	0.07	0.28	0.27	0.74	0.006	1.49	0.50	2.23	0.11	0.75	33.18
100-130	Bt3	6.60	5.30	-1.30	-	0.97	0.04	2.15	19.54	0.14	0.06	0.26	0.41	0.87	0.006	1.49	0.60	2.36	0.12	0.88	36.86
130-155	Bt4	4.90	4.30	-0.60	-	0.87	0.01	1.00	14.07	0.15	0.10	0.18	0.37	0.80	0.093	1.49	1.45	2.29	0.24	0.89	34.93
155-182	Bt5	5.00	4.40	-0.60	-	1.01	0.06	0.50	5.79	0.19	0.13	0.08	0.10	0.50	0.048	1.49	0.65	1.99	0.12	0.55	25.13
182-198	Bt6	5.30	5.10	-0.20	-	0.88	0.07	0.50	3.77	0.46	0.35	0.05	0.12	0.98	0.004	1.49	2.16	2.47	0.39	0.98	39.68
198-210+	2C	5.30	4.90	-0.40	-	1.99	0.06	0.25	10.62	2.14	1.36	0.14	0.08	3.72	0.004	1.49	7.82	5.21	0.35	3.72	71.40

Appendix Table 4 (Continued)

Depth	Horizon	pH		ΔpH	$CaCO_3$	OM	Total N	Avail. P	Avail. K	Extractable				Sum bases	Ex. Al	EA	CEC	CEC sum	CEC clay	ECEC	BS
										Ca	Mg	K	Na								
		H_2O	KCl		(%)	------ g kg^{-1}----		------- mg kg^{-1} ------		-- cmol kg^{-1}---											%
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																				
0-27/35	Ap	4.80	4.10	-0.70	-	2.83	0.09	10.94	2.65	0.15	0.05	0.03	0.10	0.33	0.105	2.23	0.75	2.56	0.30	0.44	12.89
35-46	Bt1	5.20	4.20	-1.00	-	0.94	0.05	5.88	1.76	0.11	0.04	0.02	0.37	0.54	0.115	1.49	0.80	2.03	0.20	0.66	26.60
46-63	Bt2	5.20	4.20	-1.00	-	0.63	0.05	5.56	2.02	0.10	0.04	0.03	0.11	0.28	0.101	1.49	0.65	1.77	0.16	0.38	15.82
63-80	Bt3	5.20	4.20	-1.00	-	0.61	0.04	4.40	1.91	0.07	0.03	0.02	0.07	0.19	0.118	2.23	0.70	2.42	0.20	0.31	7.85
80-100	2BC	5.00	4.10	-0.90	-	0.90	0.02	3.63	2.36	0.07	0.05	0.03	0.09	0.24	0.134	1.49	0.65	1.73	0.12	0.37	13.87
100-130	2C1	5.00	4.00	-1.00	-	1.57	0.04	3.99	3.79	0.05	0.61	0.05	0.22	0.93	0.366	2.23	5.71	3.16	0.41	1.30	29.43
130-180+	2C2	4.80	3.90	-0.90	-	1.72	0.15	1.65	11.71	1.65	1.94	0.15	0.09	3.83	0.838	3.73	5.81	7.56	0.17	4.67	50.66
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic																				
0-10/20	Ap1	5.40	5.00	-0.40	-	6.21	0.17	17.04	6.66	1.23	0.17	0.09	0.11	1.60	0.009	2.98	1.50	4.58	3.00	1.61	34.93
20-20/30	Ap2	5.30	4.40	-0.90	-	4.89	0.12	10.10	7.63	0.74	0.11	0.10	0.23	1.18	0.110	2.98	1.40	4.16	0.70	1.29	28.37
30-45	Bw	5.40	4.40	-1.00	-	1.17	0.04	1.35	2.10	0.10	0.03	0.03	0.38	0.54	0.088	1.49	0.60	2.03	1.20	0.63	26.60
45-80	Bt	5.50	4.50	-1.00	-	0.33	0.03	0.90	2.88	0.10	0.02	0.04	0.12	0.28	0.037	1.49	0.55	1.77	1.10	0.32	15.82
80-110	Btg1	5.40	4.50	-0.90	-	0.31	0.02	0.90	3.04	0.20	0.05	0.04	0.17	0.46	0.027	0.74	0.60	1.20	0.24	0.49	38.33
110-130+	Btg2	5.60	4.90	-0.70	-	0.62	0.02	0.75	2.26	0.18	0.08	0.03	0.18	0.47	0.002	1.49	0.60	1.96	1.20	0.47	23.98
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic																				
0-5	Apg	6.00	4.80	-1.20	4.16	5.50	0.21	3.90	14.58	3.39	0.76	0.19	0.46	4.80	0.028	2.98	19.98	7.78	2.32	4.83	61.70
5-23/30	Btcg	7.00	5.30	-1.70	3.77	3.30	0.14	0.52	12.26	13.60	2.79	0.15	2.25	18.79	0.001	5.21	16.71	24.00	0.47	18.79	78.29
30-48	Btg1	8.50	7.00	-1.50	3.80	1.24	0.11	0.79	15.38	18.62	3.90	0.19	0.08	22.79	0.001	1.49	20.36	24.28	0.55	22.79	93.86
48-80	Btg2	8.90	7.20	-1.70	3.66	1.03	0.11	0.95	15.60	27.03	4.81	0.19	4.71	36.74	0.001	0.74	22.23	37.48	0.55	36.74	98.03
80-113	Btg3	9.20	7.20	-2.00	3.45	0.93	0.11	4.63	17.97	18.91	5.01	0.22	0.22	24.36	0.001	1.49	24.48	25.85	0.60	24.36	94.24
113-143	Btg4	9.10	7.20	-1.90	3.45	1.00	0.12	19.01	20.55	17.67	5.66	0.25	0.28	23.86	0.001	2.98	27.80	26.84	0.66	23.86	88.90
143-162	BCg1	9.20	7.10	-2.10	3.77	1.07	0.13	77.06	21.59	21.79	6.35	0.27	1.61	30.02	0.001	1.49	27.38	31.51	0.62	30.02	95.27
162-195+	BCg2	9.10	7.10	-2.00	3.46	0.69	0.12	89.28	23.07	22.79	6.23	0.28	0.35	29.65	0.001	2.23	28.58	31.88	0.60	29.65	93.01

OM = organic matter; Ex. Al = extractable Al; EA = extractable acidity; ECEC = effective cation exchange capacity; BS = base saturation percentage

Appendix Table 5 Chemical properties of soils on Khon Buri catena

Depth	Horizon	pH		ΔpH	$CaCO_3$	OM	Total N	Avail. P	Avail. K	Extractable				Sum bases	Ex. Al	EA	CEC	CEC sum	CEC clay	ECEC	BS
										Ca	Mg	K	Na								
		H_2O	KCl		(%)	------ g kg^{-1}----		------- mg kg^{-1} ------		-- cmol kg^{-1}---											%
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic																				
0-15	Ap1	4.2	3.6	-0.6		25.01	0.66	13.15	21.52	0.49	0.03	0.28	0.08	0.88	0.65	12	9.06	12.88	0.11	1.53	6.82
15-30	Ap2	4.2	3.6	-0.6		19.23	0.61	6.49	10.73	0.54	0.02	0.14	0.10	0.80	0.57	12	6.19	12.80	0.12	1.38	6.27
30-51	Bto1	4.2	3.5	-0.7		15.02	0.28	4.24	6.22	0.30	0.22	0.08	0.21	0.81	1.04	10	9.94	10.81	0.11	1.84	7.47
51-73	Bto2	4.2	3.4	-0.8		12.72	0.24	3.74	5.04	0.18	0.11	0.06	0.06	0.41	1.39	10	6.06	10.41	0.07	1.80	3.95
73-100	Bto3	4.3	3.5	-0.8		7.99	0.26	2.50	4.33	0.14	0.11	0.06	0.08	0.39	1.16	10	7.44	10.39	0.09	1.55	3.74
100-130	Bto4	4.5	3.6	-0.9		6.85	0.30	2.45	2.94	0.10	0.25	0.04	0.12	0.51	1.03	11	7.88	11.51	0.10	1.54	4.40
130-160	Bo1	4.6	3.6	-1		4.68	0.15	1.50	3.81	0.02	0.07	0.05	0.12	0.25	0.94	8	6.44	8.25	0.08	1.19	3.06
160-185	Bo2	4.7	3.7	-1		3.29	0.18	1.30	4.48	0.01	0.04	0.06	0.23	0.34	0.87	9	5.81	9.34	0.07	1.21	3.66
185-205	Bto5	4.7	3.7	-1		5.26	0.11	1.20	3.05	0.01	0.04	0.04	0.17	0.26	0.64	7	5.94	7.26	0.07	0.90	3.58
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic																				
0-11	Ap1	6.2	5.5	-0.7		27.77	0.69	6.84	69.16	9.95	3.29	0.89	0.96	15.09	0.02	7	20.89	22.09	0.39	15.10	68.31
11-28/30	Ap2	6.2	5.4	-0.8		29.07	0.62	4.45	64.45	10.97	3.00	0.83	1.11	15.91	0.01	7	18.84	22.91	0.35	15.92	69.45
30-59	Bt1	6.2	5.4	-0.8		15.80	0.34	2.75	37.48	9.01	2.40	0.48	0.88	12.78	0.01	7	12.38	19.78	0.18	12.78	64.60
59-88	Bt2	5.2	4.5	-0.7		5.88	0.14	4.50	17.41	3.44	2.72	0.22	0.84	7.23	0.06	9	12.26	16.23	0.16	7.29	44.54
88-119	Bt3	4.5	3.9	-0.6		4.54	0.19	0.78	15.08	0.78	2.01	0.19	0.48	3.46	0.49	10	13.02	13.46	0.16	3.95	25.70
119-151	BCr1	4.4	3.9	-0.5		5.21	0.14	1.03	13.88	1.03	1.90	0.18	0.39	3.49	0.17	9	13.66	12.49	0.19	3.66	27.97
151-180+	BCr2	4.5	3.9	-0.6		4.77	0.14	0.70	8.08	0.70	1.83	0.10	0.81	3.45	0.20	8	13.32	11.45	0.23	3.65	30.15
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic																				
0-12	Ap1	6.4	5.2	-1.2		34.76	0.65	15.43	92.76	11.28	2.77	1.19	0.22	15.46	0.03	7	21.75	22.46	0.68	15.49	68.83
12-30	Ap2	6.2	5.2	-1		21.04	0.68	4.13	45.69	8.63	3.31	0.59	0.22	12.75	0.03	9	22.48	21.75	0.65	12.77	58.61
30-52	Btc1	5.0	4.2	-0.8		9.46	0.42	1.20	10.88	0.43	4.58	0.14	0.58	5.73	0.15	13	15.76	18.73	0.26	5.87	30.58
52-72	Btc2	5.0	3.8	-1.2		5.21	0.22	0.75	17.63	0.08	3.28	0.23	0.43	4.02	0.43	14	27.22	18.02	0.41	4.44	22.29
72-103	Btc3	5.0	3.7	-1.3		3.35	0.21	0.14	23.67	0.10	2.23	0.30	0.29	2.93	0.91	14	14.83	16.93	0.20	3.84	17.30
103-130	Btc4	5.0	3.5	-1.5		3.96	0.18	0.13	26.28	0.06	1.86	0.34	0.75	3.00	0.71	15	17.66	18.00	0.24	3.71	16.67
130-150	Btc5	5.0	3.4	-1.6		4.63	0.20	0.10	31.14	0.20	2.28	0.40	0.21	3.08	0.66	15	18.41	18.08	0.27	3.75	17.04
150-180	BCrt	4.8	3.4	-1.4		3.78	0.20	0.10	32.11	0.17	4.79	0.41	0.46	5.84	2.65	18	28.31	23.84	0.45	8.50	24.50
180-197+	Cr*	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = hard rock

Appendix Table 5 (Continued)

Depth	Horizon	pH		ΔpH	$CaCO_3$	OM	Total N	Avail. P	Avail. K	Extractable				Sum bases	Ex. Al	EA	CEC	CEC sum	CEC clay	ECEC	BS
										Ca	Mg	K	Na								
		H_2O	KCl		(%)	------ g kg^{-1}----		------- mg kg^{-1} ------		----------	----------	----------	----------	---------- cmol kg^{-1}	----------	----------	----------	----------	----------	----------	%
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic																				
0-15	Apg	7.6	6.3	-1.3	3.43	31.12	0.90	2.00	20.91	18.14	13.44	0.27	1.11	32.95	0.05	5	40.04	37.95	0.68	33.00	86.82
25-50	Bssg	7.8	6.3	-1.5	3.99	12.84	0.38	0.15	7.83	12.92	15.28	0.10	4.82	33.13	0.03	5	40.67	38.13	0.56	33.16	86.89
50-76	Bg1	8.0	6.4	-1.6	3.45	8.80	0.30	0.15	5.69	11.38	18.56	0.07	4.94	34.96	0.03	5	37.17	39.96	0.48	34.99	87.49
76-100/110	Bg2	8.0	6.5	-1.5	3.07	7.00	0.25	0.50	5.30	11.90	21.09	0.07	4.14	37.20	0.02	5	41.07	42.20	0.52	37.23	88.15
110-133	BCg1	8.3	6.8	-1.5	2.71	10.41	0.31	1.25	5.82	17.28	31.27	0.07	2.09	50.72	0.03	3	42.48	53.72	0.59	50.75	94.41
133-160	BCg2	8.3	7.0	-1.3	2.16	6.24	0.22	2.50	4.15	19.44	25.41	0.05	0.78	45.68	0.02	3	46.66	48.68	0.69	45.70	93.84
160-180+	Crg	8.4	7.0	-1.4	2.56	5.39	0.24	3.00	1.99	17.25	23.63	0.03	0.78	41.68	0.03	3	47.53	44.68	0.92	41.72	93.29

OM = organic matter; Ex. Al = extractable Al; EA = extractable acidity; ECEC = effective cation exchange capacity; BS = base saturation percentage

Appendix Table 6 Dithionite citrate bicarbonate, ammonium oxalate and sodium pyrophosphate extractable Fe, Al and Mn of soils on Nam Phong catena

Depth	Horizon	Fe (g kg^{-1})			Fe_o/Fe_d	Fe_p/Fe_d	Al (g kg^{-1})			Al_o/Al_d	Al_p/Al_d	Mn (g kg^{-1})			Mn_o/Mn_d	Mn_p/Mn_d
		DCB	OX	PY			DCB	OX	PY			DCB	OX	PY		
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic															
0-20	Ap	0.377	0.233	0.067	0.617	0.177	1.028	1.450	0.695	1.41	0.68	0.037	0.031	0.023	0.83	0.64
20-40	E	1.060	0.210	0.038	0.198	0.035	1.030	1.603	0.608	1.56	0.59	0.004	0.003	0.001	0.73	0.30
40-59	Bt1	5.120	0.268	0.034	0.052	0.007	1.362	1.413	0.563	1.04	0.41	0.009	0.002	0.001	0.22	0.07
59-73	Bt2	7.747	0.285	0.028	0.037	0.004	1.326	1.710	0.666	1.29	0.50	0.015	0.002	0.001	0.15	0.04
73-105	Bt3	7.056	0.209	0.019	0.030	0.003	1.307	1.254	0.597	0.96	0.46	0.013	0.002	0.000	0.12	0.01
105-142	Bt4	12.188	0.231	0.015	0.019	0.001	1.583	1.286	0.643	0.81	0.41	0.022	0.002	0.000	0.07	0.01
142-172	Bt5	11.078	0.226	0.018	0.020	0.002	1.791	1.877	0.764	1.05	0.43	0.020	0.002	0.001	0.09	0.03
172-205+	Bt6	11.244	0.210	0.019	0.019	0.002	1.607	1.325	0.686	0.82	0.43	0.023	0.002	0.000	0.07	0.00
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic															
0-23	Ap	1.432	0.202	0.080	0.141	0.056	0.694	0.709	0.615	1.02	0.89	0.017	0.016	0.008	0.94	0.48
23-35	E	1.565	0.165	0.052	0.105	0.033	0.778	0.705	0.592	0.91	0.76	0.004	0.005	0.002	1.15	0.50
35-58	Bt1	2.410	0.264	0.047	0.110	0.020	1.133	1.788	0.658	1.58	0.58	0.003	0.001	0.000	0.37	0.03
58-82	Bt2	5.055	0.318	0.045	0.063	0.009	1.391	1.452	0.631	1.04	0.45	0.004	0.002	0.000	0.50	0.07
82-110	Bt3	6.950	0.255	0.036	0.037	0.005	1.380	1.306	0.571	0.95	0.41	0.007	0.003	0.001	0.47	0.13
110-140	Bt4	7.183	0.254	0.048	0.035	0.007	1.414	1.477	0.457	1.04	0.32	0.009	0.004	0.002	0.41	0.18
140-190+	2C	12.188	0.209	0.034	0.017	0.003	0.924	0.233	0.185	0.25	0.20	0.025	0.009	0.003	0.36	0.12
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic															
0-20/30	Ap	0.897	0.140	0.080	0.156	0.089	0.485	0.355	0.345	0.73	0.71	0.014	0.012	0.009	0.83	0.62
30-45	E	1.096	0.209	0.065	0.191	0.059	0.465	0.539	0.297	1.16	0.64	0.007	0.006	0.002	0.85	0.31
45-67	Bt1	1.546	0.200	0.057	0.129	0.037	0.611	0.855	0.312	1.40	0.51	0.004	0.002	0.000	0.57	0.10
67-100	Bt2	1.751	0.220	0.053	0.125	0.031	0.704	1.077	0.352	1.53	0.50	0.002	0.003	0.001	1.05	0.40
100-130	Bt3	1.725	0.239	0.052	0.139	0.030	0.736	1.113	0.375	1.51	0.51	0.003	0.002	0.000	0.58	0.07
130-155	Bt4	2.373	0.249	0.040	0.105	0.017	0.992	1.922	0.425	1.94	0.43	0.003	0.002	0.000	0.66	0.09
155-182	Bt5	2.403	0.242	0.042	0.101	0.017	0.803	1.455	0.390	1.81	0.49	0.004	0.002	0.001	0.51	0.20
182-198	Bt6	3.072	0.267	0.051	0.087	0.017	1.014	1.558	0.392	1.54	0.39	0.013	0.013	0.007	0.96	0.53
198-210+	2C	14.470	0.350	0.053	0.024	0.004	0.867	0.192	0.154	0.22	0.18	0.041	0.026	0.005	0.64	0.13

Appendix Table 6 (Continued)

Depth	Horizon	Fe (g kg^{-1})			Fe$_o$/Fe$_d$	Fe$_p$/Fe$_d$	Al (g kg^{-1})			Al$_o$/Al$_d$	Al$_p$/Al$_d$	Mn (g kg^{-1})			Mn$_o$/Mn$_d$	Mn$_p$/Mn$_d$
		DCB	OX	PY			DCB	OX	PY			DCB	OX	PY		
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic															
0-27/35	Ap	1.394	0.332	0.134	0.238	0.096	0.702	0.726	0.378	1.03	0.54	0.011	0.014	0.005	1.31	0.47
35-46	Bt1	1.605	0.408	0.091	0.254	0.057	0.880	0.963	0.335	1.09	0.38	0.008	0.007	0.002	0.93	0.25
46-63	Bt2	1.572	0.353	0.075	0.225	0.048	0.758	0.868	0.371	1.14	0.49	0.004	0.005	0.002	1.17	0.45
63-80	Bt3	1.996	0.370	0.070	0.185	0.035	0.730	0.412	0.302	0.57	0.41	0.006	0.040	0.001	6.68	0.23
80-100	2BC	2.625	0.261	0.066	0.099	0.025	0.709	0.741	0.336	1.05	0.47	0.004	0.004	0.002	0.99	0.51
100-130	2C1	27.291	0.318	0.052	0.012	0.002	1.185	0.194	0.221	0.16	0.19	0.045	0.044	0.004	0.97	0.09
130-180+	2C2															
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic															
0-10/20	Ap1	1.142	0.333	0.248	0.292	0.217	0.628	0.725	0.288	1.15	0.46	0.032	0.005	0.024	0.15	0.76
20-20/30	Ap2	1.461	0.604	0.278	0.414	0.190	0.793	0.813	0.377	1.03	0.48	0.042	0.048	0.028	1.14	0.67
30-45	Bw	0.724	0.305	0.085	0.422	0.118	0.487	0.605	0.173	1.24	0.36	0.004	0.004	0.002	1.05	0.44
45-80	Bt	0.694	0.363	0.068	0.523	0.098	0.599	0.781	0.235	1.30	0.39	0.004	0.005	0.001	1.08	0.29
80-110	Btg1	1.167	0.333	0.060	0.285	0.052	0.773	1.098	0.275	1.42	0.36	0.007	0.009	0.003	1.27	0.38
110-130+	Btg2	1.301	0.331	0.063	0.255	0.048	0.653	0.899	0.251	1.38	0.38	0.004	0.004	0.002	0.97	0.42
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic															
0-5	Apg	2.687	1.148	0.217	0.427	0.081	1.309	1.559	0.322	1.19	0.25	0.335	0.261	0.121	0.78	0.36
5-23/30	Btcg	15.339	1.325	0.125	0.086	0.008	2.849	2.418	0.282	0.85	0.10	0.872	0.871	0.040	1.00	0.05
30-48	Btg1	9.980	0.776	0.080	0.078	0.008	1.961	1.885	0.160	0.96	0.08	0.158	0.147	0.011	0.93	0.07
48-80	Btg2	10.427	0.620	0.064	0.059	0.006	1.678	1.437	0.110	0.86	0.07	0.140	0.124	0.006	0.89	0.04
80-113	Btg3	10.679	1.035	0.070	0.097	0.007	1.692	2.082	0.150	1.23	0.09	0.499	0.505	0.006	1.01	0.01
113-143	Btg4	10.050	0.847	0.085	0.084	0.008	1.726	1.844	0.130	1.07	0.08	0.405	0.404	0.006	1.00	0.01
143-162	BCg1	11.366	0.859	0.086	0.076	0.008	1.446	1.851	0.106	1.28	0.07	0.549	0.576	0.006	1.05	0.01
162-195+	BCg2	10.934	0.730	0.072	0.067	0.007	1.417	1.252	0.080	0.88	0.06	0.583	0.559	0.005	0.96	0.01

DCB = extracted by dithionite citrate bicarbonate; OX = extracted by ammonium oxalate; PY = extracted by sodium pyrophosphate

Appendix Table 7 Dithionite citrate bicarbonate, ammonium oxalate and sodium pyrophosphate extractable Fe, Al and Mn of soils on Khon Buri catena

Depth	Horizon	Fe (g kg^{-1})			Fe_o/Fe_d	Fe_p/Fe_d	Al (g kg^{-1})			Al_o/Al_d	Al_p/Al_d	Mn (g kg^{-1})			Mn_o/Mn_d	Mn_p/Mn_d
		DCB	OX	PY			DCB	OX	PY			DCB	OX	PY		
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic															
0-15	Ap1	68.200	2.085	0.253	0.031	0.004	3.335	1.743	1.990	0.523	0.597	0.984	0.549	0.224	0.558	0.228
15-30	Ap2	75.274	1.990	0.241	0.026	0.003	3.285	1.752	1.644	0.533	0.500	1.081	0.641	0.202	0.592	0.186
30-51	Bto1	84.876	1.733	0.196	0.020	0.002	3.438	1.651	1.426	0.480	0.415	0.550	0.106	0.032	0.192	0.058
51-73	Bto2	74.724	1.541	0.104	0.021	0.001	3.175	1.718	1.386	0.541	0.437	0.506	0.071	0.016	0.140	0.032
73-100	Bto3	73.705	1.569	0.053	0.021	0.001	3.362	1.695	1.130	0.504	0.336	0.536	0.093	0.017	0.174	0.031
100-130	Bto4	82.851	1.588	0.053	0.019	0.001	3.460	1.714	0.993	0.495	0.287	0.540	0.079	0.013	0.147	0.024
130-160	Bo1	86.382	1.650	0.036	0.019	0.000	3.186	1.632	0.777	0.512	0.244	0.597	0.119	0.013	0.199	0.021
160-185	Bo2	92.629	1.325	0.030	0.014	0.000	3.222	1.615	0.679	0.501	0.211	0.678	0.180	0.023	0.265	0.034
185-205	Bto5	81.882	1.855	0.024	0.023	0.000	3.288	1.707	0.689	0.519	0.209	0.719	0.223	0.023	0.309	0.031
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic															
0-11	Ap1	23.857	2.345	0.367	0.098	0.015	2.326	2.317	0.854	0.996	0.367	2.048	1.683	0.272	0.822	0.133
11-28/30	Ap2	28.472	2.307	0.444	0.081	0.016	2.622	2.415	0.993	0.921	0.379	2.118	1.625	0.231	0.767	0.109
30-59	Bt1	41.758	2.488	0.211	0.060	0.005	3.247	2.192	0.569	0.675	0.175	1.568	0.959	0.107	0.611	0.068
59-88	Bt2	45.763	2.354	0.127	0.051	0.003	3.614	1.990	0.614	0.551	0.170	1.157	0.486	0.059	0.421	0.051
88-119	Bt3	47.510	1.857	0.106	0.039	0.002	3.939	1.967	0.581	0.499	0.148	1.016	0.372	0.068	0.366	0.067
119-151	BCr1	42.400	1.465	0.087	0.035	0.002	3.480	2.010	0.461	0.578	0.132	0.930	0.329	0.044	0.354	0.048
151-180+	BCr2	45.274	3.488	0.801	0.077	0.018	4.214	3.111	1.950	0.738	0.463	1.303	0.791	0.034	0.607	0.026
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic															
0-12	Ap1	14.685	4.195	0.462	0.286	0.031	2.218	2.695	0.744	1.215	0.336	1.548	2.069	0.397	1.336	0.257
12-30	Ap2	22.378	4.219	0.495	0.189	0.022	2.757	2.798	0.717	1.015	0.260	1.658	2.096	0.240	1.264	0.145
30-52	Btc1	43.713	3.655	0.318	0.084	0.007	4.356	3.087	0.977	0.709	0.224	1.028	1.156	0.088	1.124	0.085
52-72	Btc2	37.638	3.991	0.156	0.106	0.004	4.214	3.297	0.956	0.782	0.227	2.062	3.105	0.044	1.506	0.021
72-103	Btc3	42.615	3.855	0.144	0.090	0.003	4.261	3.422	1.013	0.803	0.238	1.866	2.683	0.024	1.438	0.013
103-130	Btc4	40.419	2.978	0.175	0.074	0.004	4.032	3.206	1.094	0.795	0.271	0.709	0.979	0.027	1.382	0.038
130-150	Btc5	41.858	2.771	0.216	0.066	0.005	3.876	2.482	1.124	0.640	0.290	0.869	0.975	0.036	1.122	0.041
150-180	BCrt	29.329	4.170	0.434	0.142	0.015	3.243	3.210	1.310	0.990	0.404	0.731	1.100	0.047	1.506	0.064
180-197+	Cr	17.107	4.278	0.541	0.250	0.032	1.373	2.428	0.430	1.768	0.313	2.057	2.598	0.027	1.263	0.013

Appendix Table 7 (Continued)

Depth	Horizon	Fe (g kg^{-1})			Fe$_o$/Fe$_d$	Fe$_p$/Fe$_d$	Al (g kg^{-1})			Al$_o$/Al$_d$	Al$_p$/Al$_d$	Mn (g kg^{-1})			Mn$_o$/Mn$_d$	Mn$_p$/Mn$_d$
		DCB	OX	PY			DCB	OX	PY			DCB	OX	PY		
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic															
0-15	Apg	34.688	8.550	0.860	0.246	0.025	1.801	1.941	0.125	1.078	0.070	1.469	1.413	0.386	0.962	0.263
25-50	Bssg	25.342	7.320	1.257	0.289	0.050	1.140	1.452	0.251	1.273	0.221	1.137	0.982	0.104	0.864	0.091
50-76	Bg1	20.171	5.851	1.195	0.290	0.059	0.980	1.428	0.343	1.457	0.350	1.001	1.071	0.064	1.069	0.064
76-100/110	Bg2	17.954	4.938	0.719	0.275	0.040	1.133	1.431	0.200	1.262	0.176	1.074	1.166	0.058	1.085	0.054
110-133	BCg1	3.381	3.430	9.077	1.014	2.685	0.619	1.730	6.185	2.794	9.990	1.309	1.758	0.036	1.343	0.027
133-160	BCg2	4.156	2.460	8.770	0.592	2.110	0.487	1.574	4.170	3.235	8.571	1.152	1.717	0.035	1.490	0.030
160-180+	Crg	3.946	1.385	4.281	0.351	1.085	0.457	1.558	1.540	3.407	3.368	0.597	0.940	0.029	1.575	0.049

DCB = extracted by dithionite citrate bicarbonate; OX = extracted by ammonium oxalate; PY = extracted by sodium pyrophosphate

Appendix Table 8 Correlation matrix among the chemical properties of soils on both catenae (marked correlations are significant at $p<0.05$)

	pH H_2O	pH KCl	OM	Total N	Avail. P	Avail. K	Ex. Ca	Ex. Mg	Ex. K	Ex. Na	Ex. Al	EA	CEC	Clay	Fe_d	Fe_o	Fe_p	Fe_o/ Fe_d	Al_d	Al_o	Al_p	Mn_d	Mn_o	Mn_p
pH H_2O	1.00																							
pH KCl	**0.97**	1.00																						
OM	0.01	0.04	1.00																					
Total N	0.08	0.10	**0.95**	1.00																				
Avail. P	**0.39**	**0.35**	0.00	0.03	1.00																			
Avail. K	0.18	0.17	**0.62**	**0.54**	0.15	1.00																		
Ex. Ca	**0.87**	**0.85**	**0.24**	**0.32**	**0.43**	**0.24**	1.00																	
Ex. Mg	**0.61**	**0.61**	0.21	**0.30**	0.05	-0.04	**0.66**	1.00																
Ex. K	0.17	0.16	**0.62**	**0.54**	0.14	**1.00**	**0.23**	-0.04	1.00															
Ex. Na	**0.52**	**0.49**	0.15	0.21	0.00	0.02	**0.55**	**0.60**	0.01	1.00														
Ex. Al	**-0.49**	**-0.59**	0.05	0.08	-0.13	-0.06	**-0.33**	-0.16	-0.06	-0.19	1.00													
EA	**-0.41**	**-0.49**	**0.41**	**0.49**	-0.13	**0.26**	-0.18	-0.01	**0.26**	-0.02	**0.70**	1.00												
CEC	**0.64**	**0.59**	**0.38**	**0.50**	0.19	0.22	**0.77**	**0.86**	0.22	**0.60**	-0.02	**0.26**	1.00											
Clay	-0.01	-0.07	**0.42**	**0.50**	0.02	0.12	**0.27**	**0.40**	0.11	**0.33**	**0.48**	**0.75**	**0.59**	1.00										
Fe_d	**-0.41**	**-0.46**	**0.38**	**0.41**	-0.08	0.01	-0.16	-0.10	0.01	-0.03	**0.62**	**0.75**	0.09	**0.81**	1.00									
Fe_o	0.19	0.14	**0.62**	**0.71**	-0.09	**0.29**	**0.34**	**0.56**	**0.29**	**0.54**	0.17	**0.55**	**0.73**	**0.65**	**0.37**	1.00								
Fe_p	**0.37**	**0.39**	0.13	0.17	-0.05	-0.08	**0.42**	**0.83**	-0.08	**0.24**	-0.11	-0.05	**0.59**	**0.25**	-0.11	**0.27**	1.00							
Fe_o/ Fe_d	**0.36**	**0.37**	0.06	0.07	-0.03	-0.10	**0.24**	**0.57**	-0.10	0.22	**-0.30**	**-0.27**	**0.33**	-0.17	**-0.41**	0.17	**0.67**	1.00						
Al_d	**-0.38**	**-0.46**	**0.35**	**0.41**	-0.08	**0.25**	-0.11	-0.15	**0.24**	-0.05	**0.56**	**0.90**	0.16	**0.76**	**0.81**	**0.43**	-0.18	**-0.45**	1.00					
Al_o	-0.03	-0.12	**0.39**	**0.46**	-0.04	**0.45**	0.17	0.14	**0.44**	0.11	**0.35**	**0.73**	**0.44**	**0.59**	**0.41**	**0.57**	0.06	-0.15	**0.78**	1.00				
Al_p	0.02	0.02	**0.24**	**0.26**	-0.12	-0.01	0.14	**0.56**	-0.01	0.04	0.20	**0.28**	**0.38**	**0.40**	0.19	**0.24**	**0.85**	**0.48**	0.16	**0.28**	1.00			
Mn_d	0.11	0.09	**0.71**	**0.76**	0.03	**0.53**	**0.35**	**0.40**	**0.53**	**0.31**	0.13	**0.65**	**0.64**	**0.71**	**0.47**	**0.77**	**0.28**	0.05	**0.64**	**0.72**	**0.37**	1.00		
Mn_o	**0.23**	0.18	**0.56**	**0.64**	0.03	**0.51**	**0.38**	**0.50**	**0.51**	**0.30**	0.06	**0.54**	**0.69**	**0.51**	0.19	**0.74**	**0.39**	0.21	**0.44**	**0.70**	**0.40**	**0.90**	1.00	
Mn_p	0.07	0.10	**0.94**	**0.93**	0.02	**0.66**	**0.28**	0.18	**0.66**	0.14	-0.05	**0.34**	**0.39**	**0.30**	**0.24**	**0.64**	0.06	0.07	**0.29**	**0.40**	0.11	**0.68**	**0.58**	1.00

Appendix Table 9 Element compositions in the whole soil of Nam Phong catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
		g kg^{-1}							mg kg^{-1}																
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic																								
0-20	Ap	5.60	459	1.17	3.70	0.22	0.17	nd	55	54	364	8.2	6.3	5.5	0.7	31.2	1.8	34.9	1.8	0.8	4.3	2.2	0.2	0.8	5.9
20-40	E	6.88	459	1.29	3.71	0.15	0.26	nd	15	27	332	8.5	9.4	5.9	0.3	11.4	1.4	17.7	2.0	1.1	4.6	2.1	0.4	0.9	6.6
40-59	Bt1	17.06	446	1.70	8.68	0.30	0.52	nd	23	45	336	9.4	22.6	12.4	0.4	33.4	7.0	16.4	4.2	2.3	9.0	3.1	0.7	1.8	10.5
59-73	Bt2	24.90	436	1.88	11.64	0.22	0.69	nd	30	58	338	10.9	31.7	15.6	0.5	35.8	4.4	23.5	5.6	3.2	11.9	3.6	0.8	2.4	15.1
73-105	Bt3	22.70	439	1.88	10.82	0.15	0.61	nd	29	50	324	11.9	30.9	16.0	0.5	21.6	4.0	27.7	5.0	3.3	10.3	2.6	0.8	2.2	13.2
105-142	Bt4	35.18	423	2.17	16.56	0.08	0.96	0.24	40	67	295	10.7	45.8	21.0	0.7	30.5	5.8	9.5	7.4	5.0	14.5	3.2	2.0	2.9	16.9
142-172	Bt5	35.56	423	2.17	16.56	0.08	0.97	0.12	37	56	307	10.5	40.6	18.9	0.6	34.6	6.0	20.2	6.9	4.2	13.5	3.3	1.8	2.8	15.0
172-205+	Bt6	33.82	425	2.10	15.90	0.08	0.96	nd	36	56	297	10.4	40.3	18.7	0.6	27.2	6.0	28.1	6.7	3.9	12.2	3.3	1.4	2.7	15.1
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic																								
0-23	Ap	4.14	462	1.44	2.28	0.15	0.34	nd	23	23	518	4.9	6.4	3.9	0.2	21.2	1.0	19.7	1.4	0.5	3.2	1.8	0.1	0.5	6.2
23-35	E	4.14	461	1.56	2.28	0.15	0.43	nd	11	13	483	4.2	6.8	3.6	0.1	35.6	1.2	21.7	1.2	0.4	3.1	1.5	0.2	0.5	6.1
35-58	Bt1	6.76	458	1.67	3.48	0.07	0.52	nd	10	21	509	6.0	10.4	6.0	0.2	36.8	6.1	19.9	2.2	0.7	4.9	2.3	0.1	0.8	8.9
58-82	Bt2	20.23	442	2.09	9.04	0.22	0.95	nd	17	51	471	6.8	25.8	15.4	0.4	33.0	5.2	16.5	4.5	2.4	11.7	4.4	0.7	1.7	15.6
82-110	Bt3	25.58	435	2.18	11.40	0.22	1.03	0.48	24	62	449	5.6	34.2	18.3	0.6	14.8	5.7	19.1	5.9	3.1	15.6	5.6	0.8	2.2	19.2
110-140	Bt4	25.62	435	2.19	11.76	0.22	1.04	nd	26	70	435	8.3	35.8	20.6	0.7	16.7	6.4	19.5	6.1	3.1	16.3	5.9	1.0	2.2	20.5
140-190+	2C	23.09	429	1.20	24.53	0.34	0.72	0.17	55	88	170	0.0	65.4	242.6	2.0	8.5	12.0	23.8	5.3	7.3	9.5	5.4	1.1	1.4	33.4
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																								
0-20/30	Ap	2.47	464	1.03	1.48	0.15	0.17	nd	20	37	524	2.3	4.7	3.6	0.3	35.9	1.4	13.2	1.1	0.5	2.5	2.2	0.2	0.3	7.0
30-45	E	2.48	463	1.09	1.60	0.07	0.25	nd	10	36	405	2.3	4.9	2.7	0.2	11.9	1.1	15.6	1.3	0.4	2.6	2.1	0.1	0.3	7.3
45-67	Bt1	3.82	462	1.22	2.28	0.07	0.34	nd	7	33	376	2.0	6.3	4.0	0.1	28.9	1.1	13.7	1.4	0.6	3.3	2.0	0.1	0.4	7.2
67-100	Bt2	4.30	461	1.29	2.57	0.07	0.43	nd	9	30	404	3.0	7.0	5.4	0.2	40.7	1.6	15.7	1.7	0.7	4.0	2.3	0.3	0.5	9.4
100-130	Bt3	4.39	461	1.25	2.49	0.07	0.43	nd	8	33	390	2.5	5.5	4.9	0.2	6.4	2.4	14.0	2.0	0.5	4.1	2.8	0.2	0.5	9.6
130-155	Bt4	6.03	459	1.34	3.47	0.07	0.43	nd	9	37	365	2.7	9.0	6.4	0.2	4.2	2.6	5.1	2.3	0.9	5.9	3.4	0.3	0.6	11.8
155-182	Bt5	5.90	459	1.36	3.61	0.07	0.43	nd	9	31	383	2.0	9.1	6.3	0.2	13.6	2.1	15.4	2.1	1.1	5.2	3.2	0.2	0.6	10.7
182-198	Bt6	7.82	457	1.53	4.30	0.15	0.52	nd	30	32	408	1.9	11.5	7.3	0.5	36.3	2.8	24.7	2.6	1.0	6.9	3.8	0.4	0.8	13.0
198-210+	2C	25.27	416	1.32	40.92	0.38	1.42	nd	83	125	210	0.0	71.9	131.9	2.6	46.7	12.5	25.9	5.3	8.2	13.1	8.7	1.5	1.3	39.3

Appendix Table 9 (Continued)

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
		g kg^{-1}							mg kg^{-1}																
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																								
0-27/35	Ap	3.39	463	0.92	2.07	0.15	0.43	nd	20	77	375	2.0	6.3	5.4	0.2	19.4	1.3	9.0	1.6	0.6	3.5	3.1	0.1	0.4	11.2
35-46	Bt1	4.27	462	1.06	2.36	0.07	0.43	nd	10	48	318	0.9	6.2	3.5	0.1	5.7	2.1	6.0	1.5	0.4	3.6	2.9	0.1	0.4	12.0
46-63	Bt2	4.22	462	1.10	2.37	0.07	0.43	nd	8	44	289	0.9	6.3	3.8	0.1	24.5	3.2	17.2	1.5	0.4	3.7	2.6	0.2	0.4	11.9
63-80	Bt3	3.79	462	1.13	2.82	0.07	0.52	nd	10	68	278	0.2	8.6	6.5	0.3	34.7	2.3	14.3	1.3	1.0	3.9	3.3	0.4	0.4	14.7
80-100	2BC	5.44	459	1.07	3.81	0.07	0.68	nd	10	63	201	1.1	9.8	6.2	0.3	24.1	2.4	10.3	1.8	1.5	4.5	4.4	0.3	0.5	19.6
100-130	2C1	20.81	367	1.28	120.20	0.15	1.20	0.65	63	284	157	0.0	123.8	307.4	4.8	10.9	43.4	68.6	7.1	32.1	5.9	3.5	7.2	0.7	49.2
130-180+	2C2																								
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic																								
0-10/20	Ap1	2.74	463	0.80	2.58	0.22	0.43	nd	40	53	280	0.3	9.6	4.5	0.3	24.7	1.4	19.8	1.2	0.6	3.0	1.9	0.2	0.2	11.1
20-20/30	Ap2	3.36	462	0.89	2.89	0.15	0.52	nd	51	49	257	0.3	9.8	4.7	0.4	20.6	1.9	6.0	1.3	1.0	3.9	2.0	0.2	0.3	9.3
30-45	Bw	2.37	464	0.90	1.67	0.07	0.34	nd	6	16	243	1.1	7.1	3.5	0.1	24.5	0.9	11.2	1.2	0.6	2.3	1.9	0.2	0.2	7.4
45-80	Bt	2.19	464	0.96	1.92	0.07	0.34	nd	6	20	224	0.6	7.7	4.5	0.1	37.2	0.9	7.2	1.1	0.7	2.3	1.9	0.1	0.2	7.9
80-110	Btg1	3.66	462	0.86	2.95	0.07	0.51	nd	11	24	180	1.2	11.2	6.0	0.3	41.6	1.5	16.7	1.5	0.5	3.6	2.1	0.4	0.3	8.7
110-130+	Btg2	2.90	463	0.77	3.39	0.15	0.43	nd	7	22	190	0.8	16.5	6.0	0.1	16.2	1.8	12.0	1.4	1.3	2.7	1.9	0.8	0.3	8.9
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic																								
0-5	Apg	16.06	441	1.64	13.43	0.60	2.52	0.78	416	64	463	8.8	27.1	21.8	5.9	13.4	7.1	35.0	5.9	2.4	16.8	3.8	0.6	1.5	20.8
5-23/30	Btcg	57.26	374	3.22	44.80	2.22	9.62	3.81	988	48	334	34.6	63.5	35.2	16.4	45.9	13.5	77.1	17.6	6.4	54.6	13.0	0.6	5.2	66.9
30-48	Btg1	55.18	381	3.33	32.60	5.56	10.43	4.39	251	21	346	29.2	44.3	31.9	6.5	45.6	10.7	71.4	14.9	3.2	51.1	15.1	0.8	4.8	20.7
48-80	Btg2	60.72	370	3.57	33.61	9.39	14.06	5.91	233	15	344	25.8	35.6	27.6	8.0	44.0	10.8	78.8	13.6	2.5	49.2	18.0	0.2	4.2	17.7
80-113	Btg3	75.46	346	4.26	41.45	5.11	21.81	9.06	40	39	285	0.0	8.8	4.3	0.3	79.6	1.7	125.8	1.2	0.9	3.1	1.9	0.2	0.2	10.9
113-143	Btg4	83.12	335	4.65	44.13	4.14	25.54	10.50	655	95	269	44.5	44.2	42.1	11.8	34.2	12.3	129.4	21.4	2.5	84.4	26.1	0.4	6.2	15.3
143-162	BCg1	86.43	327	4.75	47.83	4.89	27.24	10.96	851	175	250	46.5	49.2	44.0	13.8	67.6	14.5	145.2	23.9	3.0	89.9	29.3	3.2	6.6	17.4
162-195+	BCg2	87.44	325	4.63	47.05	8.13	27.00	11.27	864	206	253	42.8	47.5	41.8	13.4	83.6	12.8	147.4	21.8	3.0	82.8	29.5	0.4	6.3	19.6

nd = not detected

Appendix Table 10 Element compositions in the fine sand fraction of soils on Nam Phong catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
		g kg^{-1}							mg kg^{-1}																
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic																								
0-20	Ap	0.77	467.37	0.32	0.15	nd	nd	nd	2	4	35	nd	2	11	nd	0.7	4.7	4.3	0.2	nd	0.6	0.2	0.1	nd	1.9
20-40	E	0.59	466.52	0.42	0.15	nd	nd	nd	2	27	63	nd	5	12	0.06	1.3	3.4	3.1	0.2	nd	0.8	0.6	0.0	0.1	2.4
59-73	Bt2	0.63	467.16	0.33	0.07	nd	nd	nd	1	5	93	1.9	1	15	nd	1.5	2.9	6.4	0.2	nd	0.4	0.1	0.1	nd	1.7
142-172	Bt5	0.76	467.33	0.32	0.07	nd	nd	nd	1	20	75	0.6	1	12	nd	0.4	2.4	4.8	0.2	0.0	0.4	0.2	0.1	nd	1.7
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic																								
0-23	Ap	0.92	466.73	0.51	0.13	nd	nd	nd	1	nd	116	1.8	nd	14	nd	1.3	4.8	3.1	0.2	nd	0.5	0.1	0.1	nd	1.9
23-35	E	0.80	467.22	0.41	0.07	nd	nd	nd	0	5	69	nd	6	12	nd	0.2	1.5	2.7	0.3	0.3	0.6	0.3	0.6	nd	2.5
58-82	Bt2	0.90	467.22	0.47	0.00	nd	nd	nd	1	10	119	2.0	nd	6	nd	0.3	1.8	2.8	0.3	0.3	0.6	0.3	0.1	nd	2.6
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																								
140-190+	Ap	1.02	466.95	0.66	0.09	nd	nd	nd	2	7	196	nd	3	7	nd	0.4	1.3	2.9	0.4	0.4	1.0	0.4	0.1	nd	2.8
0-20/30	E	0.95	466.89	0.47	0.07	nd	nd	nd	2	15	68	nd	2	7	nd	0.5	1.8	3.0	0.4	0.3	1.0	0.4	0.1	nd	2.7
30-45	Bt2	1.11	466.52	0.48	0.14	0.08	nd	nd	3	15	97	nd	0	9	nd	0.7	1.2	2.5	0.4	0.2	0.8	0.5	0.1	0.0	3.3
67-100	Bt5	0.99	466.51	0.60	0.20	nd	nd	nd	2	9	159	nd	0	10	nd	3.1	1.2	4.0	0.4	0.0	0.9	0.6	0.3	0.0	2.7
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																								
155-182	Ap	1.04	466.57	0.57	0.21	nd	nd	nd	4	23	130	0.5	3	8	nd	2.4	7.3	7.5	0.4	0.3	1.4	0.9	0.4	0.1	3.4
198-210+	Bt2	1.20	466.77	0.46	0.16	nd	nd	nd	4	21	97	nd	6	14	nd	4.1	1.7	3.9	0.2	0.4	1.3	0.4	0.3	0.0	3.7
0-27/35	2BC	1.40	466.00	0.50	0.53	nd	0.08	nd	2	29	182	1.3	0	9	nd	0.5	2.2	3.2	0.4	0.0	1.4	0.5	0.1	0.0	4.0
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic																								
46-63	Ap1	0.92	466.51	0.42	0.69	nd	nd	nd	2	31	80	1.5	6	11	nd	0.4	1.8	3.3	0.4	0.6	0.9	0.3	0.3	nd	2.9
80-100	Bw	0.89	466.61	0.37	0.46	nd	nd	nd	0	14	60	1.8	2	8	nd	0.3	1.3	2.3	0.4	0.3	0.7	0.2	0.1	nd	3.0
100-130	Bt	0.85	467.09	0.43	0.39	0.08	nd	nd	1	5	36	0.7	5	12	nd	0.5	1.5	3.6	0.4	0.0	0.7	0.3	0.1	nd	3.0
130-180+	Btg2	0.66	466.69	0.35	1.22	nd	nd	nd	4	20	18	nd	11	13	nd	3.8	1.5	3.4	0.5	0.6	0.6	0.2	0.3	nd	3.1
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic																								
0-10/20	Apg	0.67	465.19	0.33	3.66	nd	nd	nd	65	64	111	nd	16	27	1.00	3.7	3.7	6.6	0.7	1.7	0.5	0.4	0.1	0.0	5.3
30-45	Btcg	3.23	454.87	0.47	13.22	0.08	0.29	nd	1183	218	92	1.0	27	27	15.86	4.6	6.1	13.4	5.4	3.0	2.4	1.4	0.1	0.2	75.9
45-80	Btg1	1.78	460.98	0.36	5.26	2.08	0.19	nd	266	104	74	0.8	12	17	4.31	4.1	2.8	6.8	1.5	1.2	1.0	0.8	0.1	0.0	16.4
110-130	Btg3	19.95	424.34	1.40	22.41	3.02	6.21	2.48	2167	436	233	7.8	30	22	23.57	24.3	13.6	55.2	17.9	3.7	17.7	6.6	0.4	0.9	42.2
162-195+	BCg2	28.08	401.04	1.90	34.62	8.07	8.31	3.60	5368	666	170	8.1	42	19	32.61	26.5	73.9	100.7	36.8	4.6	16.6	11.5	0.2	1.0	90.6

nd = not detected

Appendix Table 11 Element compositions in the silt fraction of soils on Nam Phong catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
		------g kg^{-1}------							------mg kg^{-1}------																
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic																								
0-20	Ap	2.39	461.81	2.79	2.46	0.15	0.27	nd	20	19	452	1.3	3.6	4.6	0.2	0.7	1.3	23	0.4	0.4	1.9	0.8	0.2	0.4	2.6
20-40	E	2.25	462.53	3.17	1.35	0.16	0.19	nd	10	21	638	nd	5.3	3.0	0.1	0.6	1.0	15	0.3	0.3	1.4	0.4	0.1	0.4	1.5
59-73	Bt2	2.29	462.45	3.75	1.45	0.10	0.22	nd	9	8	751	1.3	3.3	4.6	0.1	0.5	0.7	11	0.3	0.0	1.1	0.3	0.1	0.3	1.6
142-172	Bt5	1.98	463.04	3.05	1.33	0.07	0.17	nd	10	12	797	1.3	4.0	2.5	0.1	0.9	1.3	13	0.3	0.2	1.1	0.4	0.1	0.3	1.9
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic																								
0-23	Ap	2.83	460.24	3.92	2.69	0.16	0.56	nd	11	22	711	1.6	4.9	3.6	0.1	0.4	1.3	11	0.5	0.2	2.1	0.9	0.1	0.3	3.7
23-35	E	2.47	462.15	3.17	1.31	0.16	0.27	nd	9	7	450	nd	8.6	3.3	0.1	0.5	0.9	9	0.3	0.1	1.6	0.6	0.3	0.3	2.0
58-82	Bt2	2.23	461.96	3.50	1.66	0.15	0.26	nd	8	13	1108	1.0	3.4	1.6	0.1	0.3	0.8	9	0.3	0.2	1.7	0.4	0.1	0.3	2.4
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																								
140-190+	Ap	2.75	461.10	3.13	2.33	0.15	0.42	nd	20	30	533	1.6	4.8	2.0	0.2	0.4	1.3	15	0.5	0.1	2.4	1.2	0.1	0.3	3.8
0-20/30	E	2.86	461.06	3.28	2.61	0.18	0.52	nd	15	21	458	1.8	4.9	2.3	0.2	0.4	1.8	15	0.5	0.3	2.2	1.0	0.1	0.3	4.3
30-45	Bt2	2.78	460.14	4.46	2.48	0.16	0.46	nd	11	19	766	0.7	6.0	2.5	0.1	0.4	1.3	12	0.5	0.2	2.2	0.8	0.1	0.4	3.5
67-100	Bt5	2.68	461.24	3.77	2.09	0.09	0.43	nd	10	12	495	nd	6.5	3.6	0.1	0.3	1.0	1	0.4	0.4	2.0	0.5	0.1	0.3	2.8
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																								
155-182	Ap	2.74	461.29	3.35	2.35	0.17	0.50	nd	15	24	559	nd	10.5	3.0	0.1	0.5	1.3	13	0.5	0.4	2.2	1.1	0.3	0.3	4.4
198-210+	Bt2	2.70	460.93	3.72	2.31	0.17	0.49	nd	7	28	821	nd	6.4	3.0	0.1	0.4	1.2	15	0.4	0.3	1.9	0.9	0.0	0.3	5.6
0-27/35	2BC	3.69	459.42	3.29	3.05	0.16	0.55	nd	10	34	571	nd	8.4	5.2	0.2	0.7	1.9	22	0.6	0.8	2.2	2.7	0.2	0.3	10.1
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic																								
46-63	Ap1	2.60	461.52	3.42	1.65	0.23	0.71	nd	15	18	1261	0.3	8.1	2.0	0.1	0.3	0.9	10	0.4	0.2	1.6	0.5	0.3	0.2	4.1
80-100	Bw	2.24	462.41	3.38	1.14	0.17	0.60	nd	8	11	1094	0.6	4.8	2.4	0.1	0.5	0.9	17	0.4	0.2	1.6	0.5	0.0	0.2	4.2
100-130	Bt	2.14	462.19	3.34	1.28	0.16	0.47	nd	8	12	1294	0.7	5.0	10.4	0.1	0.8	0.9	15	0.4	0.2	1.5	0.5	0.1	0.2	4.8
130-180+	Btg2	3.09	461.09	3.14	1.44	0.17	1.29	nd	6	9	345	1.2	4.7	1.5	0.1	0.4	0.8	2	0.4	0.3	1.8	0.6	0.1	0.2	3.8
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic																								
0-10/20	Apg	3.36	459.03	3.40	3.82	0.28	0.88	nd	97	14	1103	1.2	9.3	5.4	1.2	1.2	1.0	17	0.9	0.6	1.7	0.7	0.1	0.2	7.0
30-45	Btcg	6.42	449.41	4.84	11.14	0.42	1.37	0.18	139	19	1015	1.6	13.1	7.2	2.2	2.7	2.7	50	1.4	1.1	3.0	2.0	0.1	0.3	17.6
45-80	Btg1	5.63	452.41	5.06	7.90	0.51	1.77	nd	45	20	637	1.2	10.2	7.6	0.9	3.4	2.7	35	1.0	0.9	2.8	1.8	0.1	0.3	5.9
110-130	Btg3	16.70	433.70	4.49	14.42	1.10	5.03	1.92	151	62	572	6.1	15.9	11.6	3.6	12.0	4.5	37	3.6	1.1	12.2	5.2	0.1	0.9	6.0
162-195+	BCg2	33.70	406.30	4.96	24.38	2.10	9.53	4.62	323	352	385	16.2	29.3	19.6	6.7	20.6	9.2	59	7.4	2.0	22.4	10.4	0.1	1.8	10.7

nd = not detected

Appendix Table 12 Element compositions in the clay fraction of soils on Nam Phong catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	V	Cr	Ni	Cu	Zn	Rb	Sr	Ba	Zr	Co
		---------------------------------------g kg^{-1}---------------------------------------								--mg kg^{-1}--										
	Summit: Typic Kandiustult, coarse loamy, kaolinitic, isohyperthermic																			
0-20	Ap	194.11	223.89	4.73	92.00	0.83	5.39	2.24	0.86	7.1	240	88	20	50	277	105	37	136	161	13
20-40	E	198.84	227.14	4.06	85.14	0.33	5.13	2.14	0.29	4.9	213	100	17	20	148	94	29	167	157	8
59-73	Bt2	194.64	232.51	6.71	82.19	0.16	4.98	1.57	0.17	4.5	204	78	12	19	100	85	31	109	197	2
142-172	Bt5	180.92	245.38	8.17	80.72	0.00	4.78	1.60	0.17	5.0	190	84	13	36	44	90	29	70	187	nd
	Shoulder: Psammentic Paleustalf, sandy, siliceous, isohyperthermic																			
0-23	Ap	191.26	231.81	4.60	80.81	1.41	6.76	2.95	0.71	9.7	200	103	22	35	175	115	36	211	164	22
23-35	E	199.43	227.06	3.78	82.46	0.08	6.69	2.61	0.25	7.0	234	105	9	35	129	118	40	96	141	nd
58-82	Bt2	203.44	233.20	3.88	69.26	0.49	7.02	2.34	0.08	4.6	180	92	15	30	91	133	40	182	144	7
	Upper midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																			
140-190+	Ap	190.33	235.10	3.72	77.21	1.36	7.92	2.88	0.60	12.8	180	95	12	32	164	136	23	160	126	10
0-20/30	E	192.41	233.39	4.15	76.02	1.09	7.80	3.33	0.48	8.2	173	92	4	37	214	139	38	197	154	11
30-45	Bt2	181.18	246.67	6.36	73.48	0.00	8.29	2.50	0.17	7.5	199	91	6	45	110	148	27	208	184	23
67-100	Bt5	196.98	230.54	4.40	76.93	0.09	8.52	2.59	0.16	6.2	227	105	5	51	90	146	36	150	144	6
	Lower midslope: Psammentic Haplustalf, sandy, siliceous, isohyperthermic																			
155-182	Ap	182.31	239.53	3.66	75.55	1.36	9.27	3.58	0.64	16.3	174	92	4	30	295	146	44	172	125	11
198-210+	Bt2	190.57	236.01	4.13	73.34	0.16	9.97	3.72	0.23	11.9	182	91	18	59	136	162	35	200	143	2
0-27/35	2BC	186.41	236.68	4.35	74.50	0.43	11.64	4.05	0.21	9.6	189	72	4	53	97	168	44	211	161	22
	Footslope: Oxyaquic Haplustalf, sandy, siliceous, isohyperthermic																			
46-63	Ap1	159.01	248.59	4.03	74.11	1.24	18.78	7.98	2.09	10.5	160	65	10	45	199	178	50	264	125	21
80-100	Bw	168.63	252.92	3.74	62.99	0.91	20.16	8.34	0.23	5.1	166	78	26	43	199	198	40	310	134	3
100-130	Bt	172.65	245.44	4.65	69.00	1.33	18.08	8.29	0.33	5.8	181	134	29	64	381	186	52	230	163	19
130-180+	Btg2	178.85	247.72	5.29	60.95	0.41	16.98	7.04	0.30	5.0	176	87	12	61	194	173	58	228	168	19
	Toeslope: Aeric Endoaqualf, fine, mixed, isohyperthermic																			
0-10/20	Apg	168.16	240.87	3.40	71.51	0.34	24.58	11.13	3.11	4.1	149	66	35	35	162	213	16	365	124	55
30-45	Btcg	164.59	246.98	2.82	66.24	0.25	26.56	11.72	1.14	1.7	95	91	36	31	136	223	25	334	108	35
45-80	Btg1	155.70	251.61	3.29	69.35	0.33	28.05	13.09	0.55	1.3	127	86	44	19	141	215	17	286	107	16
110-130	Btg3	148.53	255.69	2.17	61.06	0.98	38.08	16.61	0.85	0.5	89	84	50	25	174	222	26	340	108	33
162-195+	BCg2	145.39	258.72	2.13	58.99	0.98	40.32	16.89	0.89	0.7	98	72	29	23	202	246	34	399	100	15

nd = not detected

Appendix Table 13 Element concentrations in the whole soil for Khon Buri catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
(cm)		g kg^{-1}								mg kg^{-1}															
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic																								
0-15	Ap1	149	231	24	125	0.49	0.76	1.24	11.24	484	549	15	194	226	36	46	33	36	20	1.3	5	6	2.1	1.6	10
15-30	Ap2	148	232	24	125	0.49	0.66	1.30	12.24	486	571	17	200	281	38	52	36	39	22	1.3	5	7	2.4	1.7	10
30-51	Bto1	157	226	23	125	0.32	0.66	1.43	7.00	429	527	17	212	261	20	50	36	35	22	1.8	4	6	2.4	1.7	10
51-73	Bto2	157	226	24	124	0.24	0.65	1.29	6.72	385	559	20	207	206	22	58	36	39	23	1.4	4	5	2.0	1.8	10
73-100	Bto3	157	225	24	126	0.24	0.65	1.36	7.09	368	546	21	210	256	24	56	36	37	23	1.4	4	5	2.0	1.8	10
100-130	Bto4	159	224	24	125	0.16	0.65	0.95	6.80	347	539	20	199	209	22	55	37	37	22	1.4	4	5	1.8	1.7	10
130-160	Bo1	162	222	23	125	0.08	0.65	0.61	7.50	312	495	20	200	221	23	53	36	34	22	1.1	4	4	1.7	1.8	9
160-185	Bo2	165	220	23	124	0.08	0.56	1.50	7.98	305	526	23	196	195	28	63	36	38	23	1.6	5	4	1.8	1.8	9
185-205+	Bto5	163	221	23	125	0.08	0.66	1.23	8.78	288	521	21	192	223	30	56	35	35	22	1.5	4	4	1.7	1.7	9
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic																								
0-11	Ap1	132	221	25	156	2.89	1.54	1.99	21.89	638	535	18	254	211	52	97	61	74	34	1.5	13	33	1.5	1.3	11
11-28/30	Ap2	131	221	25	158	2.74	1.44	1.99	23.94	626	500	18	273	229	53	98	63	75	35	1.5	13	35	2.0	1.3	12
30-59	Bt1	147	222	24	139	1.83	1.16	1.67	14.22	471	485	18	226	183	41	86	56	58	27	1.7	13	26	1.4	1.4	8
59-88	Bt2	163	218	22	130	0.82	0.95	1.45	10.67	467	406	23	233	205	38	88	58	58	28	1.3	13	14	1.7	1.7	9
88-119	Bt3	174	218	21	118	0.50	0.87	1.60	8.84	375	373	24	194	162	31	85	49	53	27	1.1	11	9	1.4	1.7	7
119-151	BCr1	173	216	21	121	0.58	0.87	1.40	8.04	328	377	25	203	181	33	95	52	55	28	1.6	10	8	1.9	1.7	7
151-180+	BCr2	136	224	18	157	0.90	1.89	2.94	12.98	386	362	14	257	227	63	174	77	82	32	1.7	24	25	1.6	1.4	7
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic																								
0-12	Ap1	79	229	17	223	3.32	1.74	2.20	28.10	1099	543	6	414	569	77	117	79	75	30	4.4	15	27	2.2	0.8	16
12-30	Ap2	87	226	17	219	2.29	1.52	1.70	30.12	976	511	8	438	568	87	139	86	78	34	4.5	18	22	2.5	1.1	19
30-52	Btc1	121	221	18	184	0.33	1.43	2.24	17.98	652	451	12	341	488	74	155	75	69	33	3.2	25	6	1.9	1.6	15
52-72	Btc2	136	218	18	167	0.16	1.43	1.90	45.87	465	453	16	295	297	122	169	79	87	49	2.6	30	3	1.6	2.0	15
72-103	Btc3	143	223	18	151	0.08	1.53	1.78	38.88	358	447	20	268	232	106	162	75	80	45	1.8	32	3	1.2	2.3	13
103-130	Btc4	140	227	19	150	0.08	1.53	1.92	18.96	324	457	18	274	240	52	156	73	71	36	1.3	30	3	1.0	2.1	10
130-150	Btc5	133	231	20	151	0.16	1.52	2.10	14.99	228	477	11	216	195	51	125	60	57	28	1.5	23	3	0.9	1.7	6
150-180+	BCrt	123	232	20	160	0.66	1.73	2.92	16.22	247	413	13	247	242	74	148	77	74	30	1.4	19	10	0.9	1.4	5

Appendix Table 13 (Continued)

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
(cm)		---------------------------- g kg^{-1} ----------------------------------								--- mg kg^{-1} ---															
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic																								
0-15	Apg	107	266	21	119	7.25	1.63	5.48	18.85	369	427	13	193	158	56	92	52	62	24	1.1	12	56	0.9	1.2	11
25-50	Bssg	110	272	22	107	4.78	1.34	5.81	15.30	136	386	12	188	147	43	81	46	53	21	0.5	9	54	0.6	1.0	9
50-76	Bg1	102	284	21	102	3.74	1.23	6.32	14.24	86	379	11	185	148	44	78	44	49	20	0.3	8	56	0.4	0.9	10
76-100/110	Bg2	99	286	20	102	4.43	1.24	7.36	14.83	75	386	10	177	146	43	85	44	47	19	0.3	8	61	0.7	0.8	9
110-133	BCg1	87	296	18	94	11.97	1.05	11.44	20.20	61	393	10	188	155	45	83	41	50	19	0.3	7	110	0.1	0.8	8
133-160	BCg2	77	307	15	91	12.31	0.85	11.75	20.58	67	367	13	214	211	48	87	43	45	18	0.3	6	112	0.1	0.7	8
160-180+	Crg	72	317	13	88	13.43	0.65	11.48	12.44	67	338	13	259	227	44	84	43	41	16	0.6	5	111	0.1	0.6	8
Weathered basalt		106	235	17	153	6.82	7.09	10.68	35.13	205	166	5	174	237	254	210	78	130	29	1.6	3	53	0.5	0.3	3
Basaltic soil*		-	-	-	-	-	-	-	150.00	-	-	-	250	200	35	150	90	100	-	1.5	-	-	1.0	-	3

*typical published data for basaltic soils from Alloway (1995)

Appendix Table 14 Element concentrations in fine sand fraction of soils on Khon Buri catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
(cm)		---------------------------- g kg^{-1} ----------------------------------								-- mg kg^{-1} --															
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic																								
0-15	Ap1	14.06	435.27	2.87	24.68	0.40	0.00	0.00	7.88	336	195	0.4	67	259	39	9	24	17	5	1.3	0.5	2.3	0.8	0.03	9
30-51	Bto1	9.43	443.97	2.19	19.94	0.23	0.00	0.00	3.92	282	187	0.4	60	241	22	11	7	11	4	0.9	0.3	1.8	0.6	0.11	9
73-100	Bto3	10.27	442.28	2.43	21.45	0.17	0.00	0.00	4.24	244	252	1.5	58	256	30	8	8	10	5	0.4	0.2	0.9	0.9	0.03	8
130-160	Bo1	7.81	447.08	1.91	18.13	0.07	0.00	0.00	2.40	181	231	0.3	55	269	13	16	5	11	4	0.6	0.2	0.9	0.7	0.07	7
185-205	Bto5	8.45	445.86	2.03	19.27	0.19	0.00	0.00	3.66	214	271	-0.2	59	282	24	7	7	13	5	0.9	0.1	0.8	0.6	0.00	8
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic																								
0-11	Ap1	48.81	295.42	6.29	179.33	1.29	0.19	1.29	8.83	1494	318	5.2	254	294	21	53	48	58	21	4.6	1.6	7.9	1.6	0.10	11
30-59	Bt1	47.55	310.83	5.48	158.42	0.71	0.08	0.96	13.98	1626	279	2.8	281	344	32	55	51	45	20	4.8	1.9	10.6	1.9	0.13	11
88-119	Bt3	50.31	293.78	6.01	179.20	0.43	0.10	1.15	12.46	1847	248	3.3	315	350	52	56	56	44	20	4.5	1.4	3.9	2.4	0.11	14
119-151	BCr1	78.27	273.47	8.82	169.35	0.38	0.26	1.27	15.06	1800	289	6.1	328	293	38	59	62	49	24	4.5	2.5	4.3	2.4	0.34	13
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic																								
12-30	Ap2	21.56	355.48	2.73	132.28	0.71	0.00	0.40	4.39	1341	160	0.1	212	403	15	48	32	37	12	4.7	1.1	4.5	1.1	0.00	9
30-52	Btc1	24.36	348.17	3.09	138.38	0.19	0.00	0.49	8.30	1254	223	0.3	241	383	35	42	36	28	12	4.3	1.4	1.9	1.6	0.05	7
72-103	Btc3	30.21	341.77	3.50	130.91	0.15	0.09	0.58	84.04	1703	278	2.5	254	261	206	63	61	69	49	4.2	1.6	2.1	1.8	0.06	21
130-150	Btc5	23.54	347.35	4.34	137.46	0.23	0.00	0.95	18.16	1434	386	1.1	249	273	57	66	59	41	17	3.9	1.4	1.6	1.2	0.02	8
150-180	BCrt	37.66	290.08	6.41	193.62	0.53	0.18	2.69	20.76	2801	426	0.5	308	303	103	115	79	66	23	4.8	1.7	5.1	1.3	0.06	6
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic																								
0-15	Apg	35.90	355.90	4.97	96.27	6.09	0.49	2.57	9.66	2153	115	0.9	160	187	31	50	35	31	10	3.1	1.9	24.7	1.1	0.11	7
25-50	Bssg	47.65	320.94	8.19	129.66	4.16	0.70	3.25	40.23	2467	206	3.0	313	130	95	59	39	49	16	7.3	4.0	39.5	1.5	0.33	31
76-100/110	Bg2	30.32	363.43	5.32	90.83	4.68	0.28	2.52	73.40	1097	144	0.4	190	132	168	84	44	55	18	4.8	1.9	60.6	1.1	0.05	24
133-160	BCg2	11.65	411.46	2.08	32.96	22.88	0.00	2.98	51.84	869	184	0.4	109	102	59	49	15	19	10	3.9	0.7	109.5	0.6	0.02	10
160-180+	Crg	14.86	423.43	2.38	31.03	7.45	0.00	1.64	16.26	417	237	0.3	92	103	32	33	15	12	4	2.8	0.6	37.2	0.3	0.02	7

Appendix Table 15 Element concentrations in silt fraction of soils on Khon Buri catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	Zr	Li	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Pb
(cm)		g kg^{-1}								mg kg^{-1}															
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic																								
0-15	Ap1	74.77	294.45	38.41	109.96	0.40	0.64	1.94	9.60	170	944	5.4	133	118	29	30	34	42	13	0.2	2.9	3.8	0.6	0.8	5.6
30-51	Bto1	61.90	314.88	36.08	100.64	0.22	0.52	1.82	5.40	113	1548	3.8	116	107	15	24	28	37	11	0.2	1.7	2.3	0.5	0.7	4.0
73-100	Bto3	73.46	290.74	42.65	113.28	0.15	0.52	2.13	6.51	90	1485	6.2	125	110	18	25	29	37	11	0.2	1.9	2.4	0.5	0.8	4.6
130-160	Bo1	61.19	294.37	49.76	115.26	0.07	0.59	2.39	7.91	45	1528	7.5	136	123	21	27	35	45	12	0.2	1.9	2.1	0.4	0.8	5.0
185-205	Bto5	104.88	242.66	36.55	150.77	0.14	0.64	1.51	7.24	183	1325	13.4	163	131	24	38	31	36	16	0.3	2.7	2.5	1.0	1.1	6.2
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic																								
0-11	Ap1	72.35	247.04	37.41	181.26	1.94	1.08	2.36	18.82	460	844	6.6	292	172	45	71	72	70	24	1.2	4.3	22.6	1.5	0.4	9.4
30-59	Bt1	67.78	246.90	39.86	187.10	1.09	0.91	2.37	12.34	361	1022	4.9	276	159	37	63	71	69	20	0.9	3.8	15.0	1.3	0.4	7.4
88-119	Bt3	62.11	215.81	45.75	235.26	0.46	0.75	2.34	6.33	279	1151	4.7	265	155	27	57	61	55	19	0.9	2.3	5.7	1.4	0.4	6.5
119-151	BCr1	121.57	193.09	38.83	198.49	0.62	0.96	2.35	5.58	208	893	15.4	196	113	24	64	48	47	20	1.0	5.8	5.3	1.2	1.0	5.3
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic																								
12-30	Ap2	37.77	277.31	40.64	175.54	1.70	2.60	2.67	17.52	397	898	0.9	275	299	53	64	63	62	17	1.3	3.5	12.1	1.3	0.3	10.5
30-52	Btc1	27.84	302.09	46.10	149.53	0.38	1.76	2.68	6.52	230	1289	0.9	203	237	29	47	41	47	11	0.9	2.3	1.9	0.8	0.2	4.6
72-103	Btc3	31.86	299.04	47.80	148.17	0.15	0.97	2.63	11.01	124	1347	1.9	177	179	40	51	44	51	14	0.4	2.9	0.8	0.8	0.3	4.2
130-150	Btc5	38.99	280.64	48.23	164.85	0.22	1.04	2.71	11.02	119	1265	3.1	221	178	41	70	59	52	16	0.9	2.8	1.2	0.9	0.3	4.5
150-180	BCrt	67.08	258.27	42.97	168.18	0.55	3.19	2.58	9.00	139	807	3.5	216	188	50	99	65	65	17	0.7	3.0	4.2	0.8	0.3	3.0
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic																								
0-15	Apg	40.90	345.30	26.17	91.29	4.22	2.58	1.94	11.06	267	646	1.9	136	116	36	50	34	48	11	0.8	2.6	21.6	0.5	0.3	11.9
25-50	Bssg	29.80	375.82	22.55	67.39	2.70	2.26	1.71	9.27	49	680	0.8	114	92	22	35	26	28	7	0.4	1.6	17.3	0.3	0.2	8.1
76-100/110	Bg2	27.01	379.84	22.81	64.33	2.65	2.05	2.05	9.08	31	800	0.1	104	96	23	41	30	26	6	0.3	1.3	21.7	0.2	0.2	8.0
133-160	BCg2	20.75	404.98	20.33	37.60	4.47	1.97	2.08	5.34	5	621	0.0	48	52	12	19	29	18	3	0.0	0.8	25.7	0.1	0.1	6.3
160-180+	Crg	19.28	411.72	17.33	33.74	4.53	1.69	2.14	4.04	4	634	0.9	54	63	12	21	29	19	3	0.2	0.8	24.8	0.1	0.1	6.3

Appendix Table 16 Element concentrations in clay fraction of soils on Khon Buri catena

Depth	Horizon	Al	Si	Ti	Fe	Ca	K	Mg	Mn	P	V	Cr	Ni	Cu	Zn	Rb	Sr	Ba	Zr	Co
(cm)		g kg^{-1}								mg kg^{-1}										
	Crest: Rhodic Kandiustox, very-fine, kaolinitic, isohyperthermic																			
0-15	Ap1	192.70	194.32	19.05	128.81	0.00	0.57	0.89	0.85	8.4	249	132	152	77	117	18	9	0	273	61
30-51	Bto1	192.35	192.17	20.65	130.84	0.00	0.55	0.87	0.75	7.0	238	154	169	69	110	22	13	106	278	56
73-100	Bto3	192.71	192.12	20.53	130.20	0.00	0.56	0.88	0.74	6.4	221	138	152	71	84	23	6	36	287	44
130-160	Bo1	192.18	193.41	20.68	129.65	-0.08	0.57	0.76	0.82	5.4	251	128	155	64	94	27	25	10	280	48
185-205	Bto5	192.02	189.94	22.71	132.44	0.00	0.67	0.83	0.88	5.2	245	143	165	60	94	15	9	9	314	51
	Backslope: Typic Kandiustult, very-fine, kaolinitic, isohyperthermic																			
0-11	Ap1	199.17	211.14	18.73	92.79	0.34	1.18	1.36	1.07	7.3	178	92	182	69	108	32	13	109	240	68
30-59	Bt1	200.59	213.85	17.26	90.20	0.08	0.87	1.19	0.68	5.3	171	90	186	67	121	21	3	10	248	48
88-119	Bt3	207.37	218.04	14.48	78.51	0.33	0.77	1.25	0.45	3.6	159	95	192	54	90	24	20	60	187	45
119-151	BCr1	204.16	216.28	17.52	82.01	0.41	0.76	1.32	0.47	2.8	141	77	180	54	81	32	29	32	215	55
	Footslope: Typic Plinthustult, clayey-skeletal, kaolinitic, semiactive, isohyperthermic																			
12-30	Ap2	178.56	207.48	12.49	129.87	0.34	1.88	2.01	1.31	10.5	229	144	194	64	88	38	6	133	173	91
30-52	Btc1	183.33	206.64	13.17	126.81	0.00	1.72	1.83	0.68	5.7	196	122	191	93	87	51	18	17	190	59
72-103	Btc3	191.62	211.86	12.47	108.88	0.08	1.69	1.84	1.15	4.0	154	124	186	73	91	41	1	150	183	65
130-150	Btc5	189.51	215.56	12.72	105.76	0.24	1.60	1.92	0.88	2.6	168	122	182	87	89	43	3	112	180	38
150-180	BCrt	182.42	218.71	12.59	110.30	0.08	1.13	2.26	0.73	3.4	177	131	181	82	86	28	2	121	180	65
	Valley floor: Typic Endoaquert, very-fine, smectitic, active, isohyperthermic																			
0-15	Apg	159.01	230.74	16.22	111.84	3.46	0.98	5.48	1.50	5.6	175	154	129	59	116	20	27	172	214	79
25-50	Bssg	156.44	241.21	13.98	103.50	1.41	0.58	5.51	1.03	1.8	155	175	138	44	97	19	23	125	213	61
76-100/110	Bg2	142.32	248.36	15.05	107.90	1.82	0.60	8.04	1.09	1.0	165	153	114	63	74	20	22	33	197	51
133-160	BCg2	118.50	264.38	10.10	110.30	5.21	0.40	14.14	1.67	0.5	237	212	115	49	79	26	33	22	123	60
160-180+	Crg	113.51	266.61	10.45	107.98	9.66	0.30	16.16	1.51	0.4	301	234	104	60	72	9	80	51	148	66

Appendix Table 17 X-ray diffraction spacing obtained from (001) planes of layer-silicate species as related to sample treatment

Diffraction spacing (nm)	Mineral (or minerals) Indicated
	Mg-saturated, air-dried
1.4 - 1.5	Smectite, vermiculite, chlorite
0.99 - 1.01	Mica (illite), halloysite
0.72 - 0.75	Metahalloysite
0.715	Kaolinite, chlorite (2nd-order maximum)
	Mg-saturated, glyceral-solvated
1.77 - 1.80	Smectite
1.4 - 1.5	Vermiculite, chlorite
1.08	Halloysite
0.99 - 1.01	Mica (illite)
0.72 -0. 75	Metahalloysite
0.75	Kaolinite, chlorite (2nd-order maximum)
	K-saturated, air-dried
1.4 - 1.5	Chlorite, vermiculite (with interlayer aluminium)
1.24 - 1.28	Smectite
0.99 - 1.01	Mica (illite), halloysite, vermiculite (contracted)
0.72 - 0.75	Metahalloysite
0.715	Kaolinite, chlorite (2nd-order maximum)
	K-saturated, heated (550°C)
1.4	Chlorite
0.99 - 1.01	Mica, vermiculite (contracted), smectite (contracted)
0.715	Chlorite (2nd-order maximum)

Source: Whittig (1965)

APPENDIX II: SOIL PROFILE DESCRIPTION

NAM PHONG CATENA

Soil on the Summit

I **Information on the site**

Profile symbol : SU
Classification : Typic Kandiustult
Date of examination : 15 November 2002
Described by : Irb Kheoruenromne, Suphicha Thanachit, Wanida Panikorn, Punyisa Trakoonyingcharoen, Saowanuch Tawornpruek, Sumitra Watana and Tonglor Suttisong.
Location : Approximately 20 m West of Khon Kaen-Udon Thani Road (Mitraparb) at Km 38.2 Ban Nong Ya Lang Ka, Tambon Num Pong, Amphoe Num Pong, Changwat Khon Kaen.
Elevation : Approximately 210 m (MSL)
Map sheet number : 5542 I Coordination : 48 267414^{E}, 18 55617^{N}

Landform
1. Physiographic position : High terrace
2. Surrounding land form : Undulating
3. Slope on which profile site : 2% Aspect : Southwest

Land use : Cassava field and sugarcane mixed with mango, banana, *Dipterocarpus* spp. and house.

Annual rainfall : Approximately 1,209.5 mm
Mean temperature : Approximately 26.8^{o}C
Climate : Tropical Savanna

II **General information on the soil**

Parent material : Old local alluvium
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of groundwater : Deeper than 205 cm at time of sampling

III **Profile description**

Horizon	Depth (cm)	Description
Ap	0-20	Mixed brown (7.5YR 5/4) 70% and brown (7.5YR 4/3) 30%; sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, firm moist, non-sticky and non-plastic; many very fine, fine and few medium vesicular pores; common very fine and fine roots; very few variegated sands, few quartz fragments (>2mm); slightly acid (field pH 6.5); abrupt, smooth boundary to E.
E	20-40	Mixed reddish yellow (5YR 6/8) 60%, dark red (2.5YR 4/6) 30% and yellowish red (5YR 4/6) 10%; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and slightly plastic; few faint clay bridges among sand grains and few faint clay coats on ped faces and pore walls; common very fine, fine and few medium vesicular pores; few very fine and fine roots; few traces of dead roots; few charcoal fragments; neutral (field pH 7.0); abrupt, smooth boundary to Bt1.
Bt1	40-59	Red (2.5YR 5/8); sandy clay loam; moderate fine and medium

		subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; common faint clay bridges among sand grains and common faint clay coats on pore walls; common very fine, few fine and medium vesicular and few fine simple tubular pores; few very fine and fine roots; few quartz fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt2.
Bt2	59-73	Red (2.5YR 5/8); sandy clay loam; moderate fine and medium semi-angular blocky structure; hard dry, firm moist, slightly sticky and slightly plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls; common very fine, few fine and medium vesicular and few fine simple tubular pores; few very fine and fine roots; few charcoal fragments; few quartz fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt3.
Bt3	73-105	Dark red (2.5YR 4/8); sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls; common very fine, fine and few medium vesicular and few very fine and fine simple tubular pores; few very fine and fine roots; few traces of dead roots; few quartz fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt4.
Bt4	105-142	Dark red (2.5YR 4/8); sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls; common very fine, fine and few medium vesicular and few very fine and fine simple tubular pores; few very fine and fine roots; few traces of dead roots; few quartz fragments; very strongly acid (field pH 5.0); gradual, smooth boundary to Bt5.
Bt5	142-172	Dark red (2.5YR 4/8); sandy clay loam; weak to moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and slightly plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls; few very fine, common fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; few quartz fragments; few pockets of light sand krotovinas (5YR 7/8); very strongly acid (field pH 5.0); clear, smooth boundary to Bt6.
Bt6	172-205+	Dark red (2.5YR 4/8); sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, slightly firm moist, slightly sticky and moderately plastic; few faint clay bridges among sand grains and few faint clay coats on pore walls; very few very fine, common fine and few medium vesicular and few fine simple tubular pores; very few very fine and fine roots; few quartz fragments; very strongly acid (field pH 5.0).

Soil on the Shoulder

I Information on the site

Profile symbol : SH
Classification : Kandic Paleustalf
Date of examination : 16 November 2002
Described by : Irb Kheoruenromne, Suphicha Thanachit, Wanida Panikorn, Punyisa Trakoonyingcharoen, Saowanuch Tawornpruek, Sumitra Watana and Tonglor Suttisong.
Location : Approximately 50 m Northeast of Khon Kaen-Udon Thani Road (Mitraparb) at Km 38.2 Ban Nong Ya Lang Ka, Tambon Num Pong, Amphoe Num Pong, Changwat Khon Kaen.
Elevation : Approximately 207 m (MSL)
Map sheet number : 5542 I Coordination : 48 267552^{E}, 18 55638^{N}

Landform
1. Physiographic position : Shoulder slope of high terrace (Residual)
2. Surrounding land form : Undulating
3. Slope on which profile site : 7% Aspect : Northeast

Land use : Cassava field and sugarcane mixed with *Dipterocarpus* spp.

Annual rainfall : Approximately 1,209.5 mm
Mean temperature : Approximately 26.8^{o}C
Climate : Tropical Savanna

II General information on the soil

Parent material : Wash over colluvial deposits derived from sedimentary rock
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of groundwater : Deeper than 190 cm at time of sampling

III Profile description

Horizon	**Depth (cm)**	**Description**
Ap	0-23	Yellowish brown (10YR 5/4); sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, slightly firm moist, slightly sticky and non-plastic; common very fine, fine and few medium vesicular and few fine simple tubular pores; common very fine, fine and few medium roots; few fine variegated sands, few quartz fragments; neutral (field pH 7.0); abrupt, smooth boundary to E.
E	23-35	Reddish yellow (7.5YR 6/6); sandy loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and non-plastic; common very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; few fine variegated sands, few quartz fragments; neutral (field pH 7.0); abrupt, smooth boundary to Bt1.
Bt1	35-58	Mixed reddish yellow (7.5YR 6/6) 50% and yellowish red (5YR 5/8) 50%, dark red (2.5YR 4/6) band (5 cm) material runs across the horizon; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and slightly plastic; common faint clay bridges among sand grains and few faint clay coats on pore walls; few very fine, fine and few medium vesicular and few fine simple tubular pores; very few fine and medium roots; few charcoal fragments; few fine variegated sands, common quartz rock fragments; strongly acid (field pH 5.5); clear, smooth

		boundary to Bt2.
Bt2	58-82	Dark red (2.5YR 4/8); sandy clay loam; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and common prominent clay coats on pore walls; few very fine, common fine, few medium and coarse vesicular and few fine simple tubular pores; very few fine and medium roots; few traces roots; three small (4 cm) termite nests; few fine variegated sands, few quartz fragments, few fine rock fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt3.
Bt3	82-110	Dark red (2.5YR 4/8); sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on pore walls; few very fine, common fine, few medium and coarse vesicular and few fine simple tubular pores; very few fine and medium roots; three small (4 cm) termite nests; few fine variegated sands, few quartz fragments, few rock fragments (0.5-2.5 mm); very strongly acid (field pH 5.0); clear, smooth boundary to Bt4; .
Bt4	110-140	Dark red (2.5YR 4/6); sandy clay; moderate fine and medium subangular blocky structure; hard dry, firm moist, slightly sticky and moderately plastic; common distinct clay bridges among sand grains and clay coats on pore walls; few very fine, common fine and few medium vesicular and few fine simple dendritic tubular pores; practically no root; few traces of dead roots; four big (10 cm) termite nests; few fine variegated sands, few quartz fragments, few rock fragments (0.5-2.5 mm); very strongly acid (field pH 5.0); abrupt, smooth boundary to 2C.
2C	140-190+	Dark red (2.5YR 4/6); very gravely sandy clay; strong fine and medium subangular blocky structure parting along gravel surfaces; hard dry, firm moist, slightly sticky and moderately plastic; few distinct clay bridges among sand grains and few faint clay coats on pore walls and gravel surface; few very fine, fine and medium vesicular and few fine simple tubular pores; practically no root; many rock fragments various sized (up to 3 cm); strongly acid (field pH 5.5).

Soil on the Upper Midslope

I Information on the site

Profile symbol : UM
Classification : Typic Haplustalf
Date of examination : 16 November 2002
Described by : Irb Kheoruenromne, Suphicha Thanachit, Wanida Panikorn, Punyisa Trakoonyingcharoen, Saowanuch Tawornpruek, Sumitra Watana and Tonglor Suttisong.
Location : Approximately 150 m Northeast of Khon Kaen-Udon Thani Road (Mitraparb) at Km 38.2 Ban Nong Ya Lang Ka, Tambon Num Pong, Amphoe Num Pong, Changwat Khon Kaen.
Elevation : Approximately 203 m (MSL)
Map sheet number : 5542 I Coordination : 48 267604^{E}, 18 55616^{N}

Landform
1. Physiographic position : Upper midslope
2. Surrounding land form : Undulating
3. Slope on which profile site : 6% Aspect : Northeast

Land use : Cassava field and sugarcane mixed with *Dipterocarpus* spp.

Annual rainfall : Approximately 1,209.5 mm
Mean temperature : Approximately 26.8^{o}C
Climate : Tropical Savanna

II General information on the soil

Parent material : Wash and colluvium derived from sedimentary rock
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of groundwater : Deeper than 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-20/30	Mixed brown (10YR 4/3) 70% and light yellowish brown (10YR 6/4) 30%; sandy loam; weak fine and medium subangular blocky structure; soft dry, slightly firm moist, slightly sticky and non-plastic; common very fine, fine and few medium vesicular pores; common very fine, fine and few medium roots; few traces of dead roots; a streak kratovinas of dark color; neutral (field pH 7.0); abrupt, wavy boundary to E.
E	30-45	Yellowish brown (10YR 5/4); sandy loam; weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and non-plastic; common very fine, fine and few medium vesicular pores; few very fine and fine roots; few fine charcoal fragments; few fine variegated sands, few quartz fragments; neutral (field pH 7.0); abrupt, smooth boundary to Bt1.
Bt1	45-67	Reddish yellow (7.5YR 6/6), thin (1 cm) yellowish red (5YR 5/8) band; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and non-plastic; few faint clay bridges among sand grains; few very fine, common fine and few medium vesicular pores; few very fine, fine and medium roots; few traces of dead roots; few fine variegated sands, few quartz fragments; neutral (field pH 7.0); clear, smooth boundary to Bt2.
Bt2	67-100	Mixed reddish yellow (7.5YR 7/6) 80% and yellowish red (5YR 4/6)

		20%; sandy loam; weak fine and medium subangular blocky structure and strong fine and medium subangular blocky structure for red band materials; slightly hard dry, slightly firm moist, slightly sticky and non-plastic; few distinct clay bridges among sand grains and clay coats on pore walls; few very fine, common fine and few medium vesicular and few fine simple tubular pores; very few very fine and fine roots; few charcoal fragments; very few fine variegated sands, few quartz fragments, few rock fragments; strongly acid (field pH 5.5); gradual, smooth boundary to Bt3.
Bt3	100-130	Mixed reddish yellow (7.5YR 6/8) 70% and yellowish red (5YR 4/6) 30%; sandy loam; weak fine and medium subangular blocky structure and moderate fine and medium subangular blocky structure for red band materials; slightly hard dry, slightly firm moist, slightly sticky and non-plastic; few distinct clay bridges among sand grains and clay coats on pore walls; common very fine, fine and few medium vesicular and few fine simple tubular pores; two coarse roots; few traces of dead roots; few fine charcoal fragments; few fine variegated sands, few quartz fragments, few rock fragments; very strongly acid (field pH 4.5); clear, smooth boundary to Bt4.
Bt4	130-155	Mixed reddish yellow (7.5YR 6/8) 60% and dark red (2.5YR 4/8) 40%; sandy loam; moderate fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and non-plastic; few distinct clay bridges among sand grains and clay coats on pore walls; few very fine, common fine and few medium vesicular and few fine simple tubular pores; practically no roots; very few fine charcoal fragments; few fine variegated sands, few quartz fragments, few rock fragments; very strongly acid (field pH 4.5); clear, smooth boundary to Bt5.
Bt5	155-182	Mixed reddish yellow (7.5YR 6/8) 60% and dark red (2.5YR 4/8) 40%; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and slightly plastic; few distinct clay bridges among sand grains and clay coats on pore walls; common very fine, fine and few medium vesicular pores; practically no roots; few traces of dead roots; very few fine charcoal fragments; very few fine variegated sands, few quartz fragments, few rock fragments; strongly acid (field pH 5.5); clear, smooth boundary to Bt6.
Bt6	182-198	Mixed reddish yellow (7.5YR 7/6) 40%, reddish yellow (5YR 6/8) 40% and brown (7.5YR 4/3) 20%; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and slightly plastic; few distinct clay bridges among sand grains and clay coats on pore walls; few very fine, common fine and few medium vesicular pores; practically no roots; few traces of dead roots; very few fine charcoal fragments; very few very fine variegated sands, few quartz fragments, few rock fragments; slightly acid (field pH 6.5); abrupt, smooth boundary to 2C.
2C	198-210+	Mixed reddish yellow (7.5YR 7/6) 50% and dark red (2.5YR 4/8) 50%; very gravely sandy clay loam; moderate fine and medium subangular blocky structure partially parting along gravel surface; slightly hard dry, firm moist, slightly sticky and moderately plastic; few distinct clay bridges among sand grains and clay coats on pore walls; few very fine, common fine and few medium vesicular pores; practically no roots; very few very fine variegated sands, few quartz fragments, abundant rock fragments (up to 5 cm); moderately acid (field pH 6.0).

Soil on the Lower Midslope

I Information on the site

Profile symbol : LM
Classification : Typic Haplustalf
Date of examination : 15 November 2002
Described by : Irb Kheoruenromne, Suphicha Thanachit, Wanida Panikorn, Punyisa Trakoonyingcharoen, Saowanuch Tawornpruek, Sumitra Watana and Tonglor Suttisong.
Location : Approximately 220 m Northeast of Khon Kaen-Udon Thani Road (Mitraparb) at Km 38.2 Ban Nong Ya Lank ka, Tambon Num Pong, Amphoe Num Pong, Changwat Khon Kaen.
Elevation : Approximately 199 m (MSL)
Map sheet number : 5542 I Coordination : $48\ 267684^{E}$, $18\ 55702^{N}$

Landform
1. Physiographic position : Lower middle slope (high terrace)
2. Surrounding land form : Undulating
3. Slope on which profile site : 5% Aspect : East

Land use : Cassava field with sugarcane

Annual rainfall : Approximately 1,209.5 mm
Mean temperature : Approximately 26.8°C
Climate : Tropical Savanna

II General information on the soil

Parent material : Wash over colluvium and local alluvium
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of groundwater : Deeper than 185 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap	0-27/35	Brown (10YR 5/3); sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, firm moist, non-sticky and non-plastic; few very fine, common fine and few medium vesicular pores; common very fine, fine and medium roots; few traces of dead roots; few charcoal fragments; few fine variegated sands, common quartz fragments; slightly acid (field pH 6.5); abrupt, wavy boundary to Bt1.
Bt1	35-46	Mixed light yellowish brown (10YR 6/4) 75%, dark gray (10YR 4/1) 20% and strong brown (7.5YR 5/8) 5%; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and non-plastic; few faint clay bridges among sand grains; common very fine, fine and few medium vesicular pores; few very fine and fine roots; few traces of dead roots; few fine variegated sands, common quartz fragments, very few rock fragments; moderately acid (field pH 6.0); clear, smooth boundary to Bt2.
Bt2	46-63	Mixed brownish yellow (10YR 6/6) 65%, light yellowish brown (10YR 6/4) 30% and reddish yellow (5YR 6/8) 5%; sandy loam; weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and non-plastic; very few faint clay bridges among sand grains; few very fine, common fine and few medium vesicular pores; very few very fine and fine roots; few fine variegated sands, common quartz fragments; slightly acid (field pH 6.5); clear, smooth boundary

		to Bt3.
Bt3	63-80	Mixed brownish yellow (10YR 6/6) 65%, light yellowish brown (10YR 6/4) 30% and reddish yellow (5YR 6/8) 5%; slightly gravelly sandy loam; weak fine and medium subangular blocky structure; slightly hard dry, firm moist, slightly sticky and non-plastic; few faint clay bridges among sand grains; few very fine, common fine and medium vesicular pores; very few very fine and fine roots; few fine variegated sands, common quartz fragments, common fine rock fragments; strongly acid (field pH 6.0); abrupt, smooth boundary to 2BC.
2BC	80-100	Mixed reddish yellow (7.5YR 6/6) 70% and yellowish red (5YR 5/8) 30%; very gravelly sandy loam; weak fine and medium subangular blocky structure partially parting by surface of gravels; hard dry, firm moist, slightly sticky and non-plastic; very few very fine, common fine and medium vesicular pores; very few very fine and fine roots; few traces of dead roots; few fine variegated sands, many rock fragments mainly subangular shaped of various sized (up to 2 cm); slightly acid (field pH 6.5); clear, smooth boundary to 2C1.
2C1	100-130	Dark red (2.5YR 4/8); massive; practically no roots; mostly gravel massive; many rock fragments of various sized (up to 5 cm); slightly acid (field pH 6.5); clear, smooth boundary to 2C2.
2C2	130-180+	Red (2.5YR 5/8); very gravelly sandy clay; mainly massive partially strong fine and medium subangular structure; firm moist, slightly sticky and moderately plastic; common faint clay coats on pore walls; very few very fine, fine and common medium vesicular pore; practically no roots; many rock fragments of various sized (up to 2 cm); very strongly acid (field pH 4.5).

Soil on the Footslope

I Information on the site

Profile symbol : FS
Classification : Oxyaquic Haplustalf
Date of examination : 16 November 2002
Described by : Irb Kheoruenromne, Suphicha Thanachit, Wanida Panikorn, Punyisa Trakoonyingcharoen, Saowanuch Tawornpruek, Sumitra Watana and Thonglor Suttisong.
Location : Approximately 420 m Northeast of Khon Kaen-Udon Thani Road (Mitraparb) at Km 38.2 Ban Nong Ya Rung Ga, Tambon Num Pong, Amphoe Num Pong, Changwat Khon Kaen.
Elevation : Approximately 192 m (MSL)
Map sheet number : 5542 I Coordination : $48\ 267876^{E}$, $18\ 55535^{N}$

Landform
1. Physiographic position : Footslope
2. Surrounding land form : Undulating
3. Slope on which profile site : 6% Aspect : West

Land use : Cassava field and sugarcane with *Bambo* spp. mango, banana, *Dipterocarpus* spp.

Annual rainfall : Approximately 1,209.5 mm
Mean temperature : Approximately 26.8°C
Climate : Tropical Savanna

II General information on the soil

Parent material : Wash deposits
Drainage : Moderately well drained
Permeability : Moderate
Runoff : Slow
Depth of groundwater : Deeper than 130 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-10/20	Brown (10YR 4/3); sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, firm moist, non-sticky and non-plastic; common very fine, fine and few medium vesicular pores; common very fine and fine roots; few traces of dead roots; few fine variegated sands, few quartz fragments; slightly acid (field pH 6.5); clear, wavy boundary to Ap2.
Ap2	20-20/30	Dark grayish brown (10YR 4/2); sandy loam; moderately weak fine and medium subangular blocky structure; soft dry, slightly firm moist, non-sticky and non-plastic; common very fine, fine and few medium vesicular pores; common very fine and fine roots; few traces of dead roots; one small termite (1.5 cm) nest; common fine variegated sands, few quartz fragments; moderately acid (field pH 6.0); abrupt, wavy boundary to Bw.
Bw	30-45	Very pale brown (10YR 7/3) common prominent strong brown (7.5YR 5/8) mottles; sandy loam; weak fine and medium subangular blocky structure; slightly hard dry, firm moist, non-sticky and non-plastic; few very fine, common fine and few medium vesicular pores; very few very fine and fine roots; few traces of dead roots; few charcoal fragments; common fine variegated sands, few quartz fragments, few rock

		fragments; slightly acid (field pH 6.5); clear, smooth boundary to Bt.
Bt	45-80	Very pale brown (10YR 7/3) common prominent strong brown (7.5YR 5/8) mottles; sandy loam; weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, non-sticky and non-plastic; few faint clay bridges among sand grains; few very fine, common fine and few medium vesicular pores; very few very fine and fine roots; many fine variegated sands, few quartz fragments, few rock fragments; moderately acid (field pH 6.0); clear, smooth boundary to Btg1.
Btg1	80-110	Very pale brown (10YR 7/3) common distinct reddish yellow (7.5YR 6/8) and common prominent dark red (2.5YR 4/6) mottles; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, non-sticky and non-plastic; few faint clay bridges among sand grains and clay coats on pore walls, clay coats and clay bridges are partially ferri-argillan; few very fine, common fine and few medium vesicular and few fine simple tubular dendritic pores; practically no roots; common fine variegated sands, few quartz fragments, few rock fragments; moderately acid (field pH 6.0); clear, smooth boundary to Btg2.
Btg2	110-130+	Pink (7.5YR 7/4) common distinct strong brown (7.5YR 5/6) mottles; sandy loam; moderately weak fine and medium subangular blocky structure; slightly hard dry, slightly firm moist, non-sticky and non-plastic; few faint clay bridges among sand grains and clay coats on pore walls, clay coats and clay bridges are partially ferri-argillan; few very fine, common fine and few medium vesicular and few fine simple tubular dendritic pores; practically no roots; common fine variegated sands, few quartz fragments, few rock fragments; moderately acid (field pH 6.0).

Soil on the Toeslope

I Information on the site

Profile symbol	:	TS
Classification	:	Aeric Endoaqualf
Date of examination	:	17 November 2002
Described by	:	Irb Kheoruenromne, Suphicha Thanachit, Wanida Panikorn, Punyisa Trakoonyingcharoen, Saowanuch Tawornpruek, Sumitra Watana and Tonglor Suttisong.
Location	:	Approximately 870 m Northeast of Khon Kaen-Udon Thani Road (Mitraparb) at Km 38.2 Ban Nong Ya Rung Ga, Tambon Num Pong, Amphoe Num Pong, Changwat Khon Kaen.
Elevation	:	Approximately 180 m (MSL)
Map sheet number	:	5542 I Coordination : 48 268346^{E}, 18 55419^{N}

Landform

1. Physiographic position	:	Toeslope
2. Surrounding land form	:	Flat
3. Slope on which profile site	:	1% Aspect : Northeast
Land use	:	Paddy field (transplanted rice) and sugarcane on the upper slope
Annual rainfall	:	Approximately 1,209.5 mm
Mean temperature	:	Approximately 26.8°C
Climate	:	Tropical Savanna

II General information on the soil

Parent material	:	Residuum derived mainly from fine grained sedimentary rock
Drainage	:	Poorly drained
Permeability	:	Slow
Runoff	:	Slow
Flooding	:	50 cm Duration: 2-3 months
Depth of groundwater	:	Deeper than 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Apg	0-5	Brown (10YR 5/3); few distinct yellowish brown (10YR 5/8) mottles; slightly gravelly sandy clay loam; strong fine and medium semi-angular blocky structure; slightly hard dry, firm moist, very sticky and very plastic; few very fine, fine and medium vesicular pores; common very fine and fine roots; common traces of dead roots; common variegated sands, few quartz fragments, few rock fragments; moderately acid (field pH 6.0); abrupt, smooth boundary to Btcg.
Btcg	5-23/30	Mixed light yellowish brown (10YR 6/4) 50% and light gray (2.5Y 7/2) 30%; common prominent dark red (2.5YR 4/6) and common distinct white (2.5Y 8/1) mottles; gravelly silty clay; strong fine and medium subangular blocky structure; very hard dry, firm moist, very sticky and very plastic; few faint clay bridges among sand grains and few faint clay coats on pore walls; few very fine, fine and medium vesicular pores; very few very fine and fine roots; common sesquioxide concretions and nodules (7.5YR 2.5/1 and 5YR 4/3, rim of 7.5YR 4/3); few variegated sands, few quartz fragments, few rock fragments; slightly acid (field pH 6.5); abrupt, wavy boundary to Btg1.
Btg1	30-48	Olive yellow (2.5Y 6/6); many faint light gray (2.5Y 7/2), common distinct yellowish brown (10YR 5/8) and common prominent strong brown (7.5YR 5/8) mottles; silty clay; weak coarse angular blocky structure and semi-

		massive; very hard dry, very firm moist, very sticky and very plastic; few faint clay coats on pore walls; very few very fine, few fine and medium vesicular pores; practically no roots; few charcoal fragments; few fine variegated sands; neutral (field pH 7.0); clear, smooth boundary to Btg2.
Btg2	48-80	Brownish yellow (10YR 6/6); many distinct light gray (2.5Y 7/1), common faint dark gray (10YR 4/1), common distinct reddish yellow (7.5YR 6/8), common prominent yellowish red (5YR 4/6) and few faint black (10YR 2/1) mottles; silty clay; weak coarse angular blocky structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; common distinct clay coats on pore walls and some ped faces; very few very fine and fine vesicular and few fine simple tubular pores; practically no roots; few distinct pressure faces, few fine cracks; few fine variegated sands, few quartz fragments; tongue of sand materials in vertical cracks; very few fine carbonate nodules (5YR 8/1); moderately alkaline (field pH 8.0); clear, smooth boundary to Btg3.
Btg3	80-113	Light gray (5Y 7/1); many prominent brownish yellow (2.5YR 6/6), common prominent dark yellowish brown (2.5YR 4/4), common prominent brownish yellow (2.5YR 6/6) and few distinct black (10YR 2/1) mottles; silty clay; weak coarse angular blocky structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; common faint clay coats on pore walls and ped faces; very few very fine and fine vesicular and few fine simple tubular pores; practically no roots; few traces of dead roots; common distinct pressure faces, few fine cracks; few Mn-oxide accumulation soft nodules, very few fine carbonate nodules; strongly alkaline (field pH 8.5); clear, smooth boundary to Btg4.
Btg4	113-143	Light gray (5Y 7/1); many prominent brownish yellow (10YR 6/8), common prominent reddish brown (5YR 4/4) and common prominent black (5YR 2.5/1) mottles; silty clay; weak coarse angular blocky structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; common faint clay coats on pore walls and ped faces; very few very fine, fine and medium vesicular and few fine simple tubular pores; practically no roots; common faint fine pressure faces, few fine cracks; few spot accumulations of soft nodules (Mn oxide), very few fine carbonate nodules; strongly alkaline (field pH 8.5); clear, smooth boundary to BCg1.
BCg1	143-162	Light gray (5Y 7/1); many prominent brownish yellow (10YR 6/8), common prominent reddish brown (5YR 4/4) and common prominent black (5YR 2.5/1) mottles; silty clay; weak coarse angular blocky structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; few faint clay coats on pore walls and ped faces; very few fine and medium vesicular and few fine simple tubular pores; practically no roots; common distinct pressure faces of various sized, few fine cracks; very few medium carbonate nodules; strongly alkaline (field pH 8.5); clear, smooth boundary to BCg2.
BCg2	162-195+	Light gray (5Y 7/1); many prominent brownish yellow (10YR 6/8), common prominent yellowish red (5YR 4/6) and common prominent black (5YR 2.5/1) mottles; silty clay; weak coarse angular blocky structure and semi-massive; very hard dry, very firm moist, very sticky and very plastic; few faint clay coats on pore walls and ped faces; few very fine, fine and medium vesicular and few very fine and fine simple tubular pores; practically no roots; common distinct pressure faces of various sized, few fine cracks; common spot accumulations of soft nodules (manganese coated); very few large carbonate nodules; moderately alkaline (field pH 8.0).

KHON BURI CATENA

Soil on the Crest

I Information on the site

Profile symbol : CT
Classification : Rhodic Kandiustox
Date of examination : 26 January 2003
Described by : Irb Kheoruenromne, Piboon Kanghae, Suphicha Thanachit, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Wimolnan Kanket, and Thanapol Srisupha-olarn
Location : Ban Pana Nong Hin, Tambol Chae, Amphoe Khon Buri, Nakhon Ratchasima Province.
Elevation : Approximately 275 m (MSL)
Map sheet number : 5438 II Coordination : 48 0205863^{E}, 16 16056^{N}

Landform
1. Physiographic position : Top of lava corrosion plain (crest)
2. Surrounding land form : Gently undulating
3. Slope on which profile site : 0% Aspect : -

Land use : Cassava field, jackfruit and mango

Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26°C
Climate : Tropical Savanna

II General information on the soil

Parent material : Residuum derived from weathered basalt
Drainage : Well drained
Permeability : Rapid
Runoff : Slow
Depth of groundwater : Deeper than 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-15	Dusky red (10R 3/3); clay; moderate fine and medium subangular blocky structure parting to strong fine granular; slightly soft dry, slightly firm moist, slightly sticky and moderately plastic; many very fine and fine vesicular pores; many very fine and fine roots, few traces of dead roots; common fine clay balls, few fine rounded rock fragments; extremely acid (field pH 4.0); abrupt, smooth boundary to Ap2.
Ap2	15-30	Weak red (10R 4/3); clay; strong coarse angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; very few fine faint clay coats on ped faces and pore walls; many very fine, common fine and medium vesicular pores; many very fine and common fine roots; common fine clay balls, fine rounded rock fragments; extremely acid (field pH 4.0); clear, smooth boundary to Bto1.
Bto1	30-51	Dusky red (10R 3/4); clay; strong medium and coarse angular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common fine distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; many very fine and common fine roots, few traces of dead roots; few fine clay balls, fine rounded rock

		fragments; extremely acid (field pH 4.0); gradual, smooth boundary to Bto2.
Bto2	51-73	Dusky red (10R 3/4); clay; strong medium and coarse angular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common fine distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; many very fine and common fine roots, few traces of dead roots; common clay balls, few fine rounded rock fragments; extremely acid (field pH 4.0); gradual, smooth boundary to Bto3.
Bto3	73-100	Dusky red (10R 3/4); clay; strong medium and coarse angular blocky structure; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common fine distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; common very fine and fine roots, few traces of dead roots; common clay balls, few fine rounded rock fragments; very strongly acid (field pH 4.5); gradual, smooth boundary to Bto4.
Bto4	100-130	Dusky red (10R 3/4); clay; moderate fine and medium subangular blocky structure partially parting to medium and coarse granular; slightly hard dry, slightly firm moist, slightly sticky and moderately plastic; common fine faint clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; common very fine and fine roots, few traces of dead roots; common fine clay balls, very few fine rounded rock fragments; very strongly acid (field pH 4.5); clear, smooth boundary to Bo1.
Bo1	130-160	Dusky red (10R 3/4); clay; moderate fine and medium subangular blocky structure parting to coarse granular; slightly hard dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; common clay balls, very few fine rounded rock fragments; very strongly acid (field pH 4.5); gradual, smooth boundary to Bo2.
Bo2	160-185	Dusky red (10R 3/4); clay; strong fine and medium subangular blocky structure partially parting to medium and coarse granular; slightly hard dry, friable moist, slightly sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular pores; few very fine and fine roots; common clay balls, very few fine rounded rock fragments; very strongly acid (field pH 4.5); clear, smooth boundary to Bto5.
Bto5	185-205	Dusky red (10R 3/4); clay; strong fine and medium subangular blocky structure parting to fine and very fine granular; slightly hard dry, friable moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular pores; practically no roots; common clay balls, very few fine rounded rock fragments; very strongly acid (field pH 5.0)

Soil on the Backslope

I **Information on the site**

Profile symbol : BS
Classification : Typic Kandiustult
Date of examination : 25 January 2003
Described by : Irb Kheoruenromne, Piboon Kanghae, Suphicha Thanachit, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Wimolnan Kanket, and Thanapol Srisupha-olarn
Location : Ban Pana Nong Hin, Tambol Chae, Amphoe Khon Buri, Nakhon Ratchasima Province.
Elevation : Approximately 271 m (MSL)
Map sheet number : 5438 II Coordination : 48 0204480^{E}, 16 14736^{N}

Landform
1. Physiographic position : Upper backslope of undulating plain
2. Surrounding land form : Undulating
3. Slope on which profile site : 2.5% Aspect : South-West

Land use : Cassava field, sugarcane and banana

Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26^{o}C
Climate : Tropical Savanna
Others : Agricultural

II **General information on the soil**

Parent material : Colluvium and residuum derived from weathered basalt
Drainage : Well drained
Permeability : Moderate
Runoff : Moderate
Depth of groundwater : Deeper than 180 cm at time of sampling

III **Profile description**

Horizon	**Depth (cm)**	**Description**
Ap1	0-11	Dark reddish brown (5YR 3/3); clay; moderate fine and medium subangular blocky structure partially parting to strong fine granular; hard dry, firm moist, moderately sticky and very plastic; many very fine, fine and common medium vesicular pores; many very fine, fine and common medium tuberrus roots, few traces of dead roots; few clay balls, common rock fragments; slightly acid (field pH 6.5); clear, smooth boundary to Ap2.
Ap2	11-28/30	Dark reddish brown (5YR 3/3); clay; very strong medium and coarse semi-angular blocky structure; very hard dry, very firm moist, moderately sticky and very plastic; very few distinct clay coats on pore walls; common very fine, many fine and few medium vesicular pores; common very fine, fine, many medium and few coarse tuberrus roots, few traces of dead roots; few fine rounded rock fragments, traces of charcoal fragments; slightly acid (field pH 6.5); clear, smooth boundary to Bt1.
Bt1	30-59	Dark reddish brown (5YR 3/4); clay; strong fine and medium angular blocky structure; very hard dry, firm moist, moderately sticky and moderately plastic; common distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular and dendritic pores; few very fine, fine, medium and

		coarse roots; common clay balls, few fine cracks, few rock fragments, small termite nest; slightly acid (field pH 6.5); clear, smooth boundary to Bt2.
Bt2	59-88	Reddish brown (5YR 4/4); clay; strong fine and medium angular blocky structure; hard dry, firm moist, moderately sticky and very plastic; common distinct clay coats on ped faces and pore walls; many very fine, common fine and few medium vesicular and few fine simple tubular and dendritic pores; very few very fine and fine roots; common clay balls, few fine cracks, few fine rounded rock fragments; slightly acid (field pH 6.5); gradual, smooth boundary to Bt3.
Bt3	88-119	Dark red (2.5YR 4/6); clay; strong fine and medium angular blocky structure; hard dry, firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces and pore walls; many very fine, fine and few medium vesicular pores; very few very fine and fine roots, traces of dead roots; common clay balls, few fine rounded rock fragments; strongly acid (field pH 5.5); abrupt, smooth boundary to BCr1.
BCr1	119-151	Dark red (2.5YR 4/6); dusky red (2.5YR 3/2) 15% and brownish yellow (10YR 6/8) 15% gravels; very gravelly clay; moderate fine and medium semi-angular blocky structure parting along gravel surfaces; slightly hard dry, firm moist, moderately sticky and moderately plastic; very few faint clay coats on pore walls; many very fine and fine and few medium vesicular pores; very few very fine and fine roots; few clay balls, many rounded and irregular rock fragments and gravel, traces of ant’s nest; strongly acid (field pH 5.5); gradual, smooth boundary to BCr2.
BCr2	151-180+	Dark red (2.5YR 4/6); black (10YR 2/1) 20%, dusky red (2.5YR 3/2) 10% and yellow (2.5Y 7/8) 5% gravels; very gravelly clay; moderate fine and medium semi-angular blocky structure parting along gravel surfaces; slightly hard dry, firm moist, moderately sticky and moderately plastic; very few faint clay coats on pore walls; many very fine, fine and few medium vesicular pores; practically no roots; few clay balls, many rounded and irregular rock fragments and gravel; very strongly acid (field pH 5.0).

Soil on the Footslope

I Information on the site

Profile symbol : FS
Classification : Typic Plinthustult
Date of examination : 27 January 2003
Described by : Irb Kheoruenromne, Piboon Kanghae, Suphicha Thanachit, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Wimolnan Kanket, and Thanapol Srisupha-olarn
Location : Ban Pana Nong Hin, Tambol Chae, Amphoe Khon Buri, Nakhon Ratchasima Province.
Elevation : Approximately 233 m (MSL)
Map sheet number : 5438 II Coordination : $48\ 0203760^{E}$, $16\ 13994^{N}$

Landform
1. Physiographic position : Lower backslope on lava corrosion plain
2. Surrounding land form : Undulating
3. Slope on which profile site : 3.0% Aspect : Southwest

Land use : Cassava field, sugarcane and banana

Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26^{o}C
Climate : Tropical Savanna

II General information on the soil

Parent material : Colluvium and residuum derived from weathered basalt
Drainage : Well drained
Permeability : Rapid
Runoff : Moderate
Depth of groundwater : Deeper than 200 cm at time of sampling

III Profile description

Horizon	Depth (cm)	Description
Ap1	0-12	Dark reddish brown (5YR 3/3); dusky red (10R 3/4) 60% and reddish brown (5YR 4/4) 40% gravels; very gravelly clay; moderately weak medium and coarse subangular blocky structure; loose dry, slightly firm moist, slightly sticky and moderately plastic; many very fine and fine vesicular pores; many very fine, fine and common medium roots, few traces of dead roots; few clay balls, many gravels of various sizes, few ant's nest; slightly acid (field pH 6.5); clear, smooth boundary to Ap2.
Ap2	12-30	Dark reddish brown (5YR 3/3); dusky red (10R 3/4) 60% and reddish brown (5YR 4/4) 40% gravels; very gravelly clay; moderately weak medium and coarse subangular blocky structure; loose dry, slightly firm moist, slightly sticky and moderately plastic; common very fine, fine and few medium vesicular pores; many very fine, fine and common medium roots, few traces of dead roots; few clay balls, many gravels of various sizes; slightly acid (field pH 6.5); clear, smooth boundary to Btc1.
Btc1	30-52	Very dusky red (2.5YR 2.5/2); bluish black (5PB 2.5/1) 60%, dark red (2.5YR 4/6) 25% and yellowish brown (10YR 5/8) 15% gravels; very gravelly clay; moderate medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few faint clay coats on ped faces and pore walls;

		many very fine, fine and common medium vesicular pores; many very fine, fine and common medium roots; common clay balls, many rounded and subrounded gravels of various sizes; very strongly acid (field pH 5.0); clear, smooth boundary to Btc2.
Btc2	52-72	Dark red (2.5YR 3/6); bluish black (5PB 2.5/1) 80%, dark red (2.5YR 4/6) 10% and yellowish brown (10YR 5/8) 10% gravels; very gravelly clay; moderate medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; common faint clay coats on ped faces, pore walls and gravel surfaces; many very fine, fine and few medium vesicular pores; common very fine and fine roots; few clay balls, many rounded and subrounded gravels of various sizes; very strongly acid (field pH 4.5); gradual, smooth boundary to Btc3.
Btc3	72-103	Dark red (2.5YR 3/6); bluish black (5PB 2.5/1) 80%, dark red (2.5YR 4/6) 10% and yellowish brown (10YR 5/8) 10% gravels; very gravelly clay; moderate medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and very plastic; common distinct clay coats on ped faces, pore walls and gravel surfaces; many very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; few clay balls, many rounded and subrounded gravels of various sizes; very strongly acid (field pH 4.5); gradual, smooth boundary to Btc4.
Btc4	103-130	Dark red (2.5YR 3/6); bluish black (5PB 2.5/1) 80%, dark red (2.5YR 4/6) 10% and yellowish brown (10YR 5/8) 10% gravels; very gravelly clay; moderately weak medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few distinct clay coats on ped faces, pore walls and gravel surfaces; many very fine, common fine and few medium vesicular pores; few very fine and fine roots; common clay balls, few fine cracks, many rounded and subrounded gravels of various sizes; very strongly acid (field pH 4.5); clear, smooth boundary to Btc5.
Btc5	130-150	Dark red (2.5YR 4/6); bluish black (5PB 2.5/1) 50%, yellowish brown (10YR 5/8) 40% and red (10R 4/6) 10% gravels; very gravelly clay; moderately weak medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and very plastic; few distinct clay coats on ped faces, pore walls and gravel surfaces; common very fine, fine and few medium vesicular and few fine simple tubular pores; few very fine and fine roots; common fine clay balls, many rounded and subrounded gravels of various sizes; very strongly acid (field pH 4.5); clear, smooth boundary to BCrt.
BCrt	150-180	Dark reddish brown (5YR 3/4); black (10YR 2/1) 70%, yellowish brown (10YR 5/8) 20% and red (10R 4/6) 10% gravels; very gravelly clay; moderately weak medium and coarse subangular blocky structure; slightly hard dry, slightly firm moist, moderately sticky and moderately plastic; few distinct clay coats on ped faces, pore walls and gravel surfaces; many very fine, fine and few medium vesicular pores; few very fine and fine roots; common fine clay balls, many rounded and subrounded gravels of various sizes; extremely acid (field pH 4.0); clear, smooth boundary to Cr.
Cr	180-197+	Gray to light brownish gray (2.5Y 6/1-6/2); basalt texture; weathered basalt retaining massive fine grained rock structure; hard dry, firm moist, non sticky and non plastic; slightly strongly acid (field pH 6.5).

Soil on the Valley Floor

I Information on the site

Profile symbol : VF
Classification : Typic Endoaquert
Date of examination : 26 January 2003
Described by : Irb Kheoruenromne, Piboon Kanghae, Suphicha Thanachit, Saowanuch Tawornpruek, Punyisa Trakoonyingcharoen, Wimolnan Kanket, and Thanapol Srisupha-olarn
Location : Ban Pana Nong Hin, Tambol Chae, Amphoe Khon Buri, Nakhon Ratchasima Province.
Elevation : Approximately 225 m (MSL)
Map sheet number : 5438 II Coordination : 48 0203086^{E}, 16 13349^{N}

Landform
1. Physiographic position : Valley floor in lava corrosion undulating plain (toeslope)
2. Surrounding land form : Gently undulating
3. Slope on which profile site : 0% Aspect : -

Land use : Paddy field, left fallow at time of sampling, banana and coconut

Annual rainfall : Approximately 1,300 mm
Mean temperature : Approximately 26°C
Climate : Tropical Savanna
Others : Agricultural

II General information on the soil

Parent material : Colluvium and residuum derived from weathered basalt
Drainage : Poorly drained
Permeability : Slow
Runoff : Slow
Flooding depth : Irregular 40-50 cm Duration: 3-4 months
Depth of groundwater : Deeper than 100 cm at time of sampling

III Profile description

Horizon	**Depth (cm)**	**Description**
Apg	0-25	Very dark grayish brown (10YR 3/2); common fine distinct yellowish brown (10YR 5/6) and common fine prominent yellowish red (5YR 4/6) mottles; clay; moderate fine and medium subangular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; few very fine, common fine and few medium vesicular and few fine simple tubular pores; many very fine, fine and common medium roots, few traces of dead roots; few rounded rock fragments, few fine pressure faces; slightly alkaline (field pH 7.5); clear, smooth boundary to Bssg.
Bssg	25-50	Very dark gray (2.5Y 3/1); common fine faint olive brown (2.5Y 4/4) mottles; clay; weak coarse angular blocky structure and semi massive; very hard dry, very firm moist, moderately sticky and moderately plastic; common faint clay coats on tubular pore walls; few very fine and fine vesicular and common fine simple dendritic and tubular pores; few very fine and fine roots, few traces of dead roots; few clay balls; common fine pressure faces, common large slickensides; moderately alkaline (field pH 8.0); clear, smooth boundary to Bg1.
Bg1	50-76	Dark gray (2.5Y 4/1); many medium faint olive brown (2.5Y 4/3)

		mottles; clay; weak coarse subangular blocky structure and semi massive; very hard dry, very firm moist, moderately sticky and moderately plastic; very few faint clay coats on pore walls; few very fine and fine vesicular and fine simple tubular pores; very few very fine and fine roots; common clay balls, common large slickensides, few fine cracks; moderately alkaline (field pH 8.0); gradual, smooth boundary to Bg2.
Bg2	76-100/110	Dark gray (2.5Y 4/1) many medium faint dark olive brown (2.5Y 3/3) mottles; clay; moderate fine and medium subangular blocky structure; very hard dry, very firm moist, moderately sticky and moderately plastic; few very fine and fine vesicular and few very fine simple tubular pores; very few very fine and fine roots; common clay balls, few fine pressure faces, common large slickensides, few subrounded rock fragments; moderately alkaline (field pH 8.0); abrupt, smooth boundary to BCg1.
BCg1	110-133	Mixed dark greenish gray (10Y 3/1) 80% and dark olive gray (5Y 3/2) 20%; common coarse distinct yellow (5Y 7/8) mottles; clay; weak coarse angular blocky structure parting along rock structure; very hard dry, very firm moist, moderately sticky and moderately plastic; few very fine, fine and medium vesicular pores; very few very fine and fine roots; few clay balls, few fine pressure faces, few fine slickensides, few subrounded rock fragments; moderately alkaline (field pH 8.0); diffuse, smooth boundary to BCg2.
BCg2	133-160	Dark greenish gray (10Y 3/1); few fine prominent yellow (5Y 7/8) and common coarse distinct dark olive gray (5Y 3/2) mottles; clay; weak coarse angular blocky structure parting along rock structure; very hard dry, very firm moist, moderately sticky and moderately plastic; few very fine, fine and medium vesicular and few fine simple tubular pores; very few very fine and fine roots; few clay balls, few fine pressure faces, few variegated sands; moderately alkaline (field pH 8.0); clear, smooth boundary to Crg.
Crg	160-180+	Mixed very dark gray (2.5Y 3/1) 60% and dark greenish gray (10GY 3/2) 40%; dark red (2.5YR 4/8) gravels; gravelly clay; moderate fine and medium subangular blocky structure parting along rock fragments surface; very hard dry, very firm moist, slightly sticky and moderately plastic; few very fine and fine vesicular and few fine simple tubular pores; practically no roots; few fine pressure faces, few fine variegated sands; moderately alkaline (field pH 8.0).

APPENDIX III METHODS OF SOIL ANALYSES

Laboratory Analysis

Physical Analysis

Bulk Density (BD)

Bulk density is the mass of dry solid per unit bulk volume of the soil. The bulk volume includes the volume of both solid and pore space. Bulk density varies with structural condition of the soil. It is often used as a measure of soil structure. The undisturbed core samples were weighed before oven dried at 105°C overnight. The weight of the soil in core before and after oven dried and the empty core weight were used to calculate the bulk density which is reported in units of Mg m^{-3} (Blake and Hartge, 1986).

Water Retention

The tradition method of determining the water retention function involves establishing a series of equilibrium between water in the soil sample at known potential beginning at the pF of 0, 2.0, 2.5, 3.0, 3.5, 4.2, 5.6, 6.0 and 6.5.

Placed soils retained ring on the filter paper onto the kiln shelving, in the soaking tray, brought the water level to 5 mm below from base of the soil samples. Left the soils for as long as possible to wet up fully. Saturated soil was weighed and placed on saturated pressure plate. Placed the triangle plate support in the base of extraction vessel, placed the pressure plate on the triangle plate and then connected the outlet port on the plate to the port connection on the inside of the extractor vessel using a length of rubber high humidity and reduce water loss by evaporation from the soil. Equilibrium was reached when water ceased flowing from the outlet tube. A burette could be connected to the outlet tubing to accurately determine equilibrium. Time to equilibrium depends on the potential set and the soil type. When equilibrium had been reached, transfered all or part of soil in each ring to tare pre-weighed aluminum pie dishes and weighed immediately. Dry the soil at least overnight in an oven at 105°C and reweighed and calculated (Klute, 1986).

Available Water Capacity

The available water capacity (AWC) of soils is the amount of water retained in soil reservoir that can be removed by plants. The AWC was estimated by the differences between field capacity (FC, pF at 2.0) and permanent wilting point (PWP, pF at 4.2).

Particle Size Analysis

Particle size analysis was carried out to evaluate soil texture. A mass of 10 g air dried soil sample was pretreated with 30% hydrogen peroxide to remove organic matter. For dispersion of soil, the suspension was placed in a milk shake container and 10 ml of 5% sodium hexametaphosphate, a dispersing agent, was added. The volume of the contents was made up to about 200 ml with deionized water.

The contents were stirred for 15 minutes on the milk shake mixer. The contents were then sieved through a 300-mesh (0.053 mm) sieve into a one liter cylinder and volume was made up to about 200 ml with deionized water. The sand grains that remained in the sieve were dried at 105°C for overnight and weighed. The suspension in the cylinder was stirred well with an agitator in an up-down motion for 30 s. The pipette method was used as a direct sampling procedure. Twenty milliliters of suspension was pipetted out from a depth of 10 cm for clay at appropriate times based on Stoke's Law (i.e. at 28°C for <0.002 mm sized fraction sampling time at 10 cm depth is 6.5 hr). Suspensions were dried at 105°C and weighed (Kilmer and Alexander, 1949; Day, 1965). The amount of sand, silt and clay were calculated. The percentage of clay (<2 µm), silt (0.002 to 0.05 mm) and sand (0.05 to <2 mm) were plotted on ternary plots, and soils were classified using soil textural triangle classes (Soil Survey Staff, 1999).

Transferred the dry sands to the nest of sieves arranged from the top to bottom with decreasing size in the following order: 1000-, 500-, 250-, 106-, 53-µm. Shook the sieves on a sieve shaker for 3-min. Weighed each sand fraction and residual silt and clay that had passed through the 53-µm sieve.

The clay fraction for mineralogical analysis was separated using the above procedure to obtain ≈10 g of clay fraction. The clay suspension was transferred from the measuring cylinder to a plastic container, by repeated suspension and decantation, until little clay was left in suspension. The clay suspension was next flocculated by adding excess solid NaCl, and the supernatant was then decanted. The flocculated clay was transferred to a centrifuged tube to wash and remove excess salt. The procedure was repeated several times until the electrical conductivity of suspension was equal to that of the deionized water. The washed clay fraction was dried in an oven at 60 °C for further analysis. The residual silt was washed with deionized water and dried in an oven at 80 °C for further analysis.

Chemical Analysis

Soil Reaction (pH)

Soil pH was determined in water and 1N KCl at a solid to solution ratio of 1:1. The contents were stirred with a glass rod for 30 minutes and the pH was measured by a standardized pH meter (National Soil Survey Center, 1995, 1996).

Organic Matter

The organic matter content of soil was indirectly estimated through multiplication of the organic carbon concentration by 1.724. The organic carbon was determined according to the Walkley and Black wet oxidation procedure (Walkley and Black, 1934; Nelson and Sommers, 1996). This involved wet combustion of organic carbon with a mixture of potassium dichromate and sulfuric acid. After reaction the residual dichromate was titrated against ferrous sulphate. A weight of 0.5 g of soil (< 0.5 mm) was placed in a 250 ml erlenmeyer flask. Five ml of 1N $K_2Cr_2O_7$ was added and the flask was swirled gently to disperse the soil into suspension. Then 10 ml of concentrated H_2SO_4 was added to the flask, swirled gently until the soil and reagents were mixed. The solution took on a greenish cast and then changed to dark green. The flask was allowed to stand with occasional swirling for 30 minutes. Then 30 ml of deionized water was added to the flask, swirled gently then 3-4 drops of o-phenanthroline indicator were added and the solution was titrated with 1N $FeSO_4$ until the color changed to a red end point.

Total N

One gram of finely ground soil was digested by potassium sulfate-catalyst mixture (mixed up of the ground K_2SO_4, $CuSO_4.H_2O$ and selenium into the conc. H_2SO_4 at the ratio of 1:1:5) stood in the digestion block at 400 ^{o}C for 60 min and then allowed to cool. The cool mixture was made up to 50 ml and filtered with No. 42 Whatman filter paper. The filtrates were transferred to Kjeldahl flask to which 25 ml of 50% NaOH was added. Five ml of 4% boric acid was placed into a 100 ml flask. The Kjeldahl flask was connected to the distillation unit and the boric solution flask with condenser, and was then distilled for 45 min. The solution was titrated with 0.1 H_2SO_4 drop by drop until color change from pink to green end point. The volume of H_2SO_4 was recorded and used to calculate the total N as g kg^{-1}.

Available Phosphorus

Three grams of soils were extracted by 30 ml of the Bray II solution, shaking for 40 sec. and then filtered with No. 42 Whatman filter paper. Dissolved 12 g ammonium molybdate in 250 ml deionized water, dissolved 0.2908 g antimony potassium tartrate in 100 ml deionized water, mixed two solution into the 1L of 2.5 M H_2SO_4 and finally made up to 2L with deionized water, as reagent A. The reagent B is made by dissolving ascorbic acid in 200 ml reagent A. Pipetted 1-10 ml of the filtrate into the 25 ml volumetric flask. Added 4 ml reagent B and finally made up to 25 ml with deionized water allowing to stand for 30 min for the constant color in the solution. Light transmittance was measured with a spectrophotometer at 882 μm and phosphorus determined by reference to a standard curve.

Extractable Bases

The bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) that are extracted by NH_4OAc extraction are generally exchangeable bases located on the cation exchange sites of the soil (Thomas, 1987a). A weight 5 g of soil was placed in an erlenmeyer flask and approximately 50 ml 1N NH_4OAc, at pH 7.0, was added, swirled and allowed to stand overnight. The contents were then filtered using a Buchner funnel with No. 42 Whatman filter paper and a 250-ml suction flask. The volume of the extract was made up to 100 ml. The extracts were analyzed for Ca, Mg, Na and K using AAS.

Extractable Acidity

Extractable acidity is the acidity released from the soil by barium chloride-triethanolamine solution buffer ($BaCl_2$-TEA) at pH 8.2 (Thomas, 1987b). It includes all acidity generated by replacement of the hydrogen and aluminum ions from permanent and pH-dependent exchange sites. A soil sample weighing 5 g was placed in an erlenmeyer flask and 15 ml of buffer solution at 8.2 (0.5N $BaCl_2.H_2O$ and 0.2 N triethanolamine) were added. The contents were stirred and allowed to equilibrate for 30 min before filtering using the Buchner funnel procedure. The contents were given

3 additional washings with 20 ml buffer solution and 5 washing with 20 ml of the replacing solution (0.5N $BaCl_2.H_2O$ and 0.4 ml of buffer solution in 1L). The volume of the extracts was made up to 100 ml and 5 drops of mixed indicator (bromocresol green and methyl red in 95% ethyl alcohol) were added. The extract was titrated with 0.17N HCl. The acid was added drop by drop until the color changed from green to an end point of purplish red color. The amount of HCl consumed was used to calculate the extractable acidity expressed as cmol H^+ kg^{-1}.

Extractable Al

Extractable Al is exchangeable aluminum extracted by 1N KCl. It is a major constituent of exchangeable cations only in strongly acid soils with pH less than 5.0. It contributes to the effective cation exchangeable capacity (ECEC). A soil sample weighing 10 g was placed in 125 ml erlenmeyer flask and 15 ml of 1N KCl were added. The contents were stirred and allowed to equilibrate for 30 min. The contents were filtered by the Buchner funnel procedure and washed 3 times with 5-10 ml 1N KCl before making the volume to 100 ml. Five ml of aliquot were pipetted into a 50-ml volumetric flaks, to which 2 ml of 1% thioglycolic acid and 10 ml of aluminon reagent were added before making the volume to 50 ml with deionized water. The contents were placed in a boiling-water bath for 4 min and cooled down to room temperature, and then transferred to reading tube. Light transmittance was measured with a spectrophotometer at 535 μm and Al determined by reference to a standard curve (McLean, 1965; Bertsch and Bloom, 1996).

Cation Exchange Capacity (CEC)

The CEC is defined as the sum of the exchangeable cations that a soil can adsorb. It is dependent upon the negative charges of soil components. Two main methods of CEC determination were used (Rhoades, 1982; Chapman, 1965; National Soil Survey Center, 1995, 1996):

CEC by NH_4OAc at pH 7.0 was determined by saturating the exchange sites with an index cation (NH_4^+), washing the soil free of entrained index cation, displacing the index cation (NH_4^+) adsorbed by soil and measuring the index cation. Five grams of soil were placed in an erlenmeyer flask, to which 50 ml of 1N NH_4OAc, pH 7.0 were added. The flask was stirred occasionally and allowed to stand overnight. The contents were filtered by the Buchner funnel procedure. The soil was then given 5 washings with 10 ml of 1N NH_4OAc, 5 washings with 25 ml 1N NH_4Cl, pH 7.0 and 6 washings with 25 ml of 95% ethyl alcohol. The aliquots from these washings were discarded. The index cation was next displaced by giving 5 washings with 25 ml of 10% acidified NaCl, and filtrates were collected in filtering flasks. The filtrates were transferred to Kjeldahl flask to which 25 ml of 50% NaOH were added. Five ml of 4% boric acid were placed into a 100 ml flask. The Kjeldahl flask was connected to the distillation unit and the boric solution flask with condenser, and was then distilled for 45 min. The solution was titrated with 0.1 H_2SO_4 drop by drop until color changed from pink to the green end point. The volume of H_2SO_4 was recorded and used to calculate the CEC as cmol kg^{-1}.

Base Saturation

Base saturation is the percentage of total exchangeable bases relative to CEC. Base saturation percentage for cations displaced by NH_4OAc at pH 7.0 is equal to the sum of bases extracted by NH_4OAc, divided by the CEC determined by NH_4OAc, and multiplied by 100 (National Soil Survey Center, 1995, 1996).

Dithionite-Citrate-Bicarbonate (DCB) Extractable Fe, Al and Mn

The amounts of Fe extracted from soils by various dissolution methods (so called specific reagents) are commonly taken to indicate particular forms of these elements in soil. The results are useful in studies of soil classification, genesis and behavior. Dithionite-citrate-bicarbonate removes finely divided hematite, goethite, lepidocrocite, ferrihydrite and non-crystalline Fe-oxide minerals. The method extracts virtually no Fe or Al from most crystalline silicate minerals, and thus provides an estimate of “free oxide” (i.e. non-silicate Fe, Al and Mn) in soils.

One gram of soil (< 0.5 mm) was weighed into a 100 ml centrifuge tube to which 45 ml of buffer solution (0.3M Na-citrate + 0.1M Na-bicarbonate) were added. The tube was then placed in a water bath at 80 °C. One gram of Na-dithionite powder was added to the tube, the mixture was stirred constantly for 1 min and occasionally during next 15 min. Ten ml of NaCl saturated solution and 10 ml acetone were added to promote flocculation. The tube contents were centrifuged for 15 min at 2000 rpm. Clear supernatant was decanted into a 250 ml volumetric flask. This extraction procedure was repeated twice, then the volume was made up to 250 ml with deionized water and the solution was kept for further analysis. For determination of Fe, Al and Mn by AAS, standard solutions of these elements were prepared in a matrix of extracting solution (Mehra and Jackson, 1960).

Oxalate Extractable Fe, Al and Mn

The oxalate procedure was used to remove sesquioxide weathering products from soils. It was revised by Schwertmann (1964), who showed that it could be used to estimate non-crystalline and poorly crystalline Fe and Al forms in soils (Ross and Wang, 1993). In principle, the sample is shaken with a complexing acidic ammonium oxalate solution dissolving the active or poorly crystalline compounds of Fe, Al, and Mn, which are determined for the extract by AAS.

A subsample of one gram of soil (< 0.5 mm) was weighed into a 250 ml centrifuge tube. Fifty ml of 0.2M ammonium oxalate solution at pH 3.0 were added to the tube. The tube was shaken for 4 h in darkness. Then five drops of 0.4% Superfloc were added to the tube, which was swirled and centrifuged. Clear supernatant was kept for further analysis by AAS. (McKeague and Day, 1966; Hodges and Zelazny, 1980).

Pyrophosphate Extractable Fe, Al and Mn

In addition to crystalline oxides and silicates of Fe, Al and Mn, various organic complexes occur in soils. Pyrophosphate solution has been used to extract organic complexes of Fe, Al and Mn (McKeague, 1967; Loveland, 1984).

A subsample of 1 g of soil (< 0.5 mm) was weighed into a 200 ml shaking tube and 100 ml of 0.1M sodium pyrophosphate solution were added before shaking overnight. Fifty ml of solution were transferred into a 50 ml centrifuge tube, 3 drops of 0.4% Superfloc were added, and mixed thoroughly before centrifuging the tubes. Clear supernatant was kept for measuring Fe, Al, and Mn by AAS.

X-ray Fluorescence (XRF) for Whole Soils, Silt, Clay and Fine Sand Samples

Major and minor element concentrations in whole soil, fine sand, silt and clay samples were determined using a Philips PW1400 XRF spectrometer fitted with a rhodium tube. A 0.700 g of finely ground sample was fused with 7.000 g of lithium meta/tetraborate flux at 1050°C in a platinum crucible. The molten mixture was cast into a disc in a platinum-gold alloy mold. The elemental compositions were determined by comparison with certified reference materials and the minimal spectrometer drift corrected by regular measurement of an external monitor sample. Matrix effects were corrected using α-factors provided by Philips and adjusted for this sample preparation procedure (Norrish and Hutton, 1969; Jones, 1987; Karathanasis and Hajek, 1996).

Inductively Coupled Plasma-Mass Spectrometry

Trace element content of separated samples was determined using inductively coupled plasma-mass spectrometry (ICP-MS). For aqua regia digestion, 0.2 g of finely ground whole soil, fine sand, silt and clay samples were dissolved in 2 ml of conc. HNO_3 and 6 ml of conc. HCl at 95-100^{o}C for 4 h. The volume was made to 20 ml with MilliQ 18MW water before filtering it with No. 42 Whatman filter paper into acid washed vials. The 0.5 ml aliquots of the digestions were made up to the 10 ml mark with a 10 ppb rhodium internal standard (1:20 dilution ratio) acidified solution (1%HNO_3) with <2% TDS (total dissolved solids), using an automated dilutor. An analysis was carried out on a Perkin Elmer Elan 6000 ICP-MS for V^{51}, Cr^{52}, Co^{59}, Ni^{60}, Cu^{65}, Zn^{66}, Cd^{114}, Pb^{208}. Blanks and standard samples were analyzed at the beginning and the end of each sample run. Additional blanks and 200 ppb multi-element standards were included after every 25 samples and analyzed as for the samples (Lynch, 1999; Soltanpour *et al.*, 1996).

Aluminum, Si, Ti, Fe, Ca, Mg, K, Mn and Zr of finely ground soil, fine sand, and silt, were determined by XRF on fused lithium tetraborate discs. Phosphorus, Li, Cs, As, Cr, V, Ni, Rb, Cu, Zn, Ga, Co, Pb, Mo, Zr, U and Sr were determined by ICP-MS on acid digests of finely ground soil, fine sand, and silt. For the clay fraction, Al, Si, Ti, Fe, Ca, Mg, K, Mn, P, Ni, Zr, Rb, Sr, Zn, Cu, Co, Cr, Ba and V were determined by XRF.

Mineralogical Analysis

X-Ray Diffraction (XRD) for Bulk Soil Samples

X-ray diffraction analysis was used to identify and to make semi-quantitative measurements of the crystalline mineral components of soil, especially for the clay fraction and iron oxide concentrate. Semi-quantitative mineral are reported as dominant (>60%), large (40-60%), moderate (20-40%), small (5-20%) and trace (<5%).

The mineral component of clay, silt and fine sand fractions were identified. The clay fraction from sedimentation was pretreated using 4 treatments: 1) Mg^{2+} saturation, 2) Mg^{2+} saturation and glycerol solvation, 3) K^+ saturation, 4) K^+ saturation and heating at 550°C to preferentially orient the clay minerals (Brown and Brindley, 1980). The clay after Mg^{2+} and K^+ saturation was dropped on the ceramic porous plates, sprayed with ≈10% glycerol on the Mg^{2+} saturation slide for the glycerol treatment, and heated to 550 °C on K^+ saturation slide for heat treatment. XRD of the clay samples was carried out using a Philips PW-3020 diffractometer with a graphite diffracted beam monochromater (CuKα operating at 50 KV and 20 mA). Clay fractions were scanned from 3 to 40° 2θ, using a step size of 0.02° 2θ and a scan speed of 0.02° 2θ sec^{-1}. Relative proportions of various minerals were calculated by comparing the XRD peak intensity with the intensity for standard minerals (Whittig, 1965; Klug and Alexander, 1974; Brindley and Brown, 1980).

Random powder XRD patterns of silt and grounded fine sand samples were scanned from 4-70° 2θ using a scan speed of 0.02° min^{-1} on Philips PW-3020 diffractometer equipped with a graphite diffracted beam monochromater (CuKα operating at 50 KV and 20 mA). A semi-quantitative estimate of the relative proportions of minerals was obtained by comparing the ratio of integrated intensities of major reflections. Relative proportions of various minerals were calculated by comparing XRD peak intensities with the intensities of standard minerals. The following reflections were used as they were distinct and free of major interferences: 104 hematite, 110 goethite, 001 kaolinite, 101 quartz, 002 illite, 101 anatase, 220 feldspar and 002 gibbsite. Minor corrections of spacing for peak shifts due to instrumental error were made by reference to reflections due to quartz, which was normally present in all samples (Klug and Alexander, 1974).

The Identification of Smectite Mineral Group

Generally, a smectite mineral group in soils consists of montmorillonite, beidellite and nontronite. To separate montmorillonite from beidellite and nontronite normally uses Greene-Kelley method, Li saturated clay heats at 200-300 °C, which has already been developed (Greene-Kelley, 1953). Fifty milligrams of clay were transferred into 30-ml test tube and washed 3 times with aqueous 3M LiCl and 2 times with 0.01M LiCl in 90% methanol. Dropped the Li-saturated clay suspension on the ceramic porous plate under a slow vacuum. The clay on the ceramic plate was allowed to dry slowly at 25°C and then heated overnight at 250°C in a muffle furnace. Curling of the clay film during heating, if it occurred, was prevented by wrapping thin bands of aluminum foil tightly around the edges of the clay coated ceramic plate before heating (Brindley and Ertem, 1971). Placed it in the desiccators until it cool, the clay was examined by XRD. Then placed it in the sealed glass container containing glycerol for solvation and heated in an oven at 90°C for 26 hr. The clay was then analyzed by XRD. The XRD of the clay samples was carried out using a Philips PW-3020 diffractometer with a graphite diffracted beam monochromater (CuKα operating at 50 KV and 20 mA) with scanned from 3 to 40° 2θ, using a step size of 0.02° 2θ and a scan speed of 0.02° 2θ sec^{-1}. The irreversible collapse of an expanding mineral to 0.95 nm after saturation with Li^+ and heating at 200-300 ^oC was the criterion for identification of the monmorillonite. On the other hand, the expansion to 1.78 nm with glycerol after Li-treatment and drying was the criterion for characterizing the mineral as beidellite (Greene-Kelley, 1953; Lim and Jackson, 1986; Singh and Gilkes, 1991).

Clay Suspension under the Transmission Electron Microscope (TEM)

One milliliter of sample in the clay suspension was transferred into the 10-ml test tube, mixed well with 9 mL of the deionized water. Placed the tube into the ultrasonic bath for 15-30 min to disperse the clay in the solution. A drop of the clay suspension is on the carbon coated grid and allowed it dry in the air then examined under the transmission electron microscope to examine their size and shape of the mineral in the clay fraction.

Analysis of Polished Thin sections

Optical Analysis

Undisturbed soil samples of selected horizons were impregnated with a 50:50 resin:monostryrene mixture and 5 g of the catalyst benzoyl peroxide ($C_{14}H_{10}O_4$). The resin mixture was poured onto samples at atmospheric pressure, followed by a period in a vacuum oven at 60 ^oC while the pressure was slowly increased from 10 to 65 cm Hg, and then the samples were left for 4 hours. The dried impregnated samples were cut into 0.5 cm thick slabs using a diamond saw and polished with corundum abrasives from 250 mesh down to 600 mesh. After ultrasonic cleaning, the polished samples were mounted onto glass slides followed by polishing and hand-finishing to produce thin sections of 0.03 mm thickness. The thin sections were analyzed under a polarizing microscope using standard micromorphological techniques as described by Bullock *et al.* (1985).

Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) Microanalysis

The polished thin section samples were first analyzed by optical microscopy. The areas of interest were selected and coated with carbon for examination using a backscattered electron image and elemental mapping on a JEOL 6400 SEM operated at 15kV of electron beam accelerating voltage. Electron microprobe analysis (EMPA) and energy dispersive spectrometer (EDS) quantitative microanalysis were used to determine the chemical composition of distinct micromorphological features (White and Dixon, 1995).

Analysis of Sand Grain Surface

The fine sand fraction (0.25-0.1 mm) of the samples was selected and examined. In general, fine sand grains are the most useful for determination of their surface. They are large enough to show the surficial features of interest, not yet so large as to be composed of more than one material (Darmony, 1985). The iron oxides cement between the grains were removed by the dithionite citrate bicarbonate, washed with DI water and then oven dried at 80 ^oC. Up to 100 fine sand grains were mounted on an aluminum stub with the double carbon tapes and coated with platinum of about 20 nm thick before examining under the 6400 JEOL SEM to characterize the roundness class. The machine was operated at 15 kV. Randomly 20 fine sand grains were characterized for detailed surface features by taking a photograph in full view and then their edges and faces were photographed at a higher magnification. The surface features are reported in term of abundant (>75%), common (35-75%), present (5-35%), few (1-5%) and absent (0%).

Statistical Analysis

Correlation Matrix

The Statistica program (version 6.1) was applied to analyse the relationship among the chemical properties on both catenae which the marked correlations are significant at $p < 0.05$.

Factor Analysis

The concentrations of elements in the whole soil, sand, silt and clay were statistically analyzed using canonical analysis, factor analysis and principal component analysis with the Statistica program (version 6.1). Factor analysis, a widely used multivariate statistical method, was employed to interprete data. This technique reveals the correlation structure of the geochemical variables allowing the identification of affinity groups of elements and samples. Also, this method was applied to identify the affinity groups of chemical properties of the soil samples (Balakrishnan and Bhaumik, 1994; Evans *et al.,* 1996; Bakac and Kumru, 2001; Kumru and Bakac, 2003)

Graphical Sorting Parameter

Particle size distribution curves for soils were expressed on a Φ scale. Folk and Ward’s (1957) graphical method was adopted to calculate mean size (M_z), sorting (σ_I), skewness (SK_I) and kurtosis (K'_G). This method involves the measurement of several percentiles from cumulative curves (Φ5, Φ16, Φ25, Φ50, Φ75, Φ84 and Φ95). The formulae are as follows:

$$\Phi = -\log_2 G \quad \text{where G = the grain size (mm)}$$

(i.e. sieve mesh opening)

Mean size $$M_z = \frac{\Phi 16 + \Phi 50 + \Phi 84}{3}$$

Sorting $$\sigma_I = \frac{\Phi 84 - \Phi 16}{4} + \frac{\Phi 95 - \Phi 5}{6.6}$$

Skewness $$SK_I = \frac{\Phi 16 + \Phi 84 - 2\,\Phi 50}{2(\Phi 84 - \Phi 16)} + \frac{\Phi 5 + \Phi 95 - 2\,\Phi 50}{2(\Phi 95 - \Phi 5)}$$

Kurtosis $$K'_G = \frac{\Phi 95 - \Phi 5}{2.44(\Phi 75 - \Phi 25)}$$

These parameters aid in the characterization of the samples by providing a concise summary of particle size distribution and thus providing a basis for an interpretation of the environments of transport and deposition. The mean size indicates the average kinetic energy of the deposition agent and is also dependent upon the size distribution of the available source materials. Sorting is an indicator of fluctuations in kinetic energy of the transporting medium during deposition. Skewness of the particle size distribution is a measure of asymmetry and marks the position of the mean size with respect to the median size. Negative skewness values indicate that the mean size of the sediment is towards the coarser side of the median whereas the positive skewness values shows that the mean is towards the finer side of the median. Kurtosis is a measure of the ratio of sorting within the central 90% of the distribution curve to sorting of the central 50% and is sometimes described as a measured of peakedness (Sahu, 1964).